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The Use of Hypermedia to Support Team-based Maintenance of Manufacturing Systems

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ABSTRACT

The research described in this thesis is concerned with the use of information technology to reduce manufacturing system downtime. The work was sponsored by Ford Motor Company Ltd, and the pilot information system was evaluated and demonstrated in their Bridgend engine plant. The maintenance strategy followed in this factory is total productive maintenance (TPM).

Downtime reduction can offer significant benefits to a manufacturer through increases in capacity at no extra cost. Many organisations have implemented computerised maintenance management systems (CMMS) to improve their maintenance business processes, but studies have shown that CMMS have often delivered few real benefits. Although CMMS can assist the management of maintenance, they are under threat in this respect from more generic software such as enterprise resource planning (ERP). Studies have shown that within manufacturing organisations most CMMS users are managers, but very seldom production operators. CMMS have been accused of being too technology-centred and may therefore be unsuitable where a human-centred philosophy such as TPM is used.

A pilot hypermedia information system has been designed and evaluated with the collaboration of maintenance managers and the work force of the engine plant. A version of the system was developed to investigate the use of a digital manual for data capture. The results of usability trials suggest that hypermedia manuals will be accepted and used by factory personnel in TPM teams, and that such a manual can be easily updated to provide an asset history. A hypermedia manual has been shown to enable knowledge management since knowledge gained during the process life-cycle may be added to that provided in the manual by the process designers.

The main benefit of a hypermedia maintenance manual is rapid access to information, which can reduce the duration of unplanned maintenance activities.

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GLOSSARY OF TERMS

AI	Artificial intelligence
BMP	Bitmap
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CALS	Continuous acquisition and life-cycle support
CBM	Condition-based maintenance
CMMS	Computerised maintenance management system
EDM	Engineering data management
EMA	Expert maintenance advisor
EPSS	Electronic performance support system
ERP	Enterprise resource planning
FMEA	Failure modes and effects analysis
FMECA	Failure modes, effects and criticality analysis
FPS	Ford production system
FTPM	Ford total productive maintenance (Ford terminology)
HCI	Human-computer interaction
HTML	Hypertext markup language
IETM	Interactive electronic technical manual
IGES	Initial graphics exchange specification
IMT	Integrated manufacturing team (Ford terminology)
IT	Information technology
ITTS	Interactive task support system
KBS	Knowledge-based system
MMIS	Maintenance management information system
MRF	Maintenance request form (Ford terminology)
OEE	Overall equipment effectiveness
PDA	Personal digital assistant
PDF	Portable document format
PDM	Product data management
PM	Planned maintenance
RCM	Reliability-centred maintenance

SGML	Standard generalised markup language
SMS	Scheduled maintenance system (Ford terminology)
SPL	Single point lesson
STS	Socio-technical systems
TAM	Technology acceptance model
TEM	Total equipment maintenance (Ford terminology)
TIFF	Tagged image file format
TPM	Total productive maintenance
WWW	World-wide web

1. Introduction

1.1 Maintenance and Information Systems

This thesis investigates the use of information technology to support the team-based maintenance of manufacturing systems. The research process included the design of a pilot information system that was used to demonstrate and evaluate the approach chosen in a factory belonging to the Ford Motor Company Ltd. Although the design and development of the information system was influenced by Ford's requirements and priorities, it is felt that the knowledge generated during this project is applicable to many maintenance activities involving teams both within the automotive industry and elsewhere.

1.2 Scope of Research

Maintenance activities take place in any organisation operating plant and equipment that embodies technology. There are many approaches to maintenance that may be adopted depending on the consequences of a breakdown in terms of cost or risk to life. Although some techniques are common to a range of industry sectors, some are only found in the particular environments for which they were originally developed. Inevitably the operators of a nuclear power station will adopt a different approach to maintenance from a housing association who may be responsible for the safe operation of domestic central heating systems, although poor maintenance may lead to loss of life in both cases. Examples from industry include the utility companies who must maintain a network of pipes, pumping stations and treatment plants; the airlines who must maintain fleets of aircraft and their engines; as well as manufacturing industry for whom maintenance usually means optimising the availability of manufacturing processes.

The research described in this thesis is most relevant to manufacturing industry although some of the ideas were originally developed outside this environment. Furthermore the research is most relevant to those manufacturers who are following the current trend of adopting a team-based approach to maintenance known as total productive maintenance (TPM). Although this is most common in the automotive industries, where much of the research described in this thesis took place, team-based maintenance is by no means limited to this environment.

1.3 The Ford Motor Company

The following section briefly describes part of the history of the Ford Motor Company. Appendix A contains a more detailed description of this history and the central role of the Ford Motor Company in the automotive industry.

1.3.1 Henry Ford

Henry Ford was born in 1863, the son of a Michigan farmer. Against his father's wishes he left the farm to become an apprentice toolmaker. After completing his apprenticeship, he married and returned to the farm where he experimented with petrol engines. He became famous in 1903 when his racing car *999* broke the land speed record, and he used this fame to launch the Ford Motor Company in the same year.

Whilst other automobile companies made vehicles for the wealthy, Ford's goal from early on was to mass produce a means of transport for the general public - this was the famous Model T (Hidy and Cawein, 1967).

1.3.2 Highland Park and The Rouge

The Model T was announced in 1908, and in 1909 Ford opened the first phase of a new factory at Highland Park. As output of the Model T increased and the manufacture of components was brought in-house from sub-contractors the Highland Park factory expanded. There was a culture of experimentation at Highland Park that led to the development of many innovations in production engineering including the moving assembly line. Although the concept of mass production had originated in the bicycle industry and the assembly line was pioneered by Ford's competitor Olds, it was at Highland Park that these techniques were perfected. They were used to bring the cost of the Model T within reach of the men who made it (Ford, 1926).

Demand for the Model T allowed and required the construction of another factory. This was a very large highly integrated plant situated on the River Rouge. 'The Rouge' as it became known allowed Ford to reduce the full lead-time for a Model T (raw material to car in a dealer's showroom) to 4 days. Ford's production achievements were widely publicised and the world's car manufacturers, including the Japanese, copied his techniques (Hidy and Cawein, 1967).

1.3.3 Automation

Between the wars, The Ford Motor Company was severely weakened by internal power struggles and industrial relations disputes. The company and its factories deteriorated to the extent that the US government considered nationalisation, but in 1945 Henry Ford's wife Clara and the widow of his son Edsel (Edsel had died two years earlier) forced Ford to hand control over to his grandson Henry II. Henry II set about re-building the company and appointed Delmar Harder as vice president of manufacturing (Hidy and Cawein, 1967).

Harder claimed to have coined the term *automation* which he defined as "the automatic handling of parts between progressive production processes" (Harder, 1954). He oversaw the installation of many new machine tools at Ford including transfer machines. Harder initiated the construction of the highly automated Cleveland Engine Plant and listed the benefits of what became known as 'Detroit Automation' as lower costs and higher output, quality and safety. He accepted the penalty for using such technologies as the need to pay far greater attention to maintenance. The Cleveland Engine Plant featured many innovations to improve maintenance (Harder, 1954) such as the following:

- A data collection and cost control system based on punched cards
- The adoption of standards for machine design
- The use of planned maintenance
- The decentralisation of the maintenance department into area teams each of which reported to production supervisors for their area.

1.3.4 Japanese techniques

In 1950, when Eiji Toyoda returned from his study tour of The Rouge he reported that there was no great difference between Ford and Toyota in terms of manufacturing technology and production methods. If anything, he felt that Toyota might be ahead with their just-in-time system. He felt that if Toyota modernised their factories and invested in the latest equipment, they should be able to surpass Ford (Nonaka and Takeuchi, 1995).

History has proved him right to the extent that Western manufacturers now visit Japanese companies on study tours to try and learn the secrets of their success. The adoption of Japanese working practices in Western companies has been called *Japanisation* and Wilkinson and Oliver (1990) use this term to describe its effect upon Ford in the UK. Examples of the changes at Ford are the 1985 reduction in job classifications from 550 to 52 and the introduction of multi-skilling and teamworking.

1.3.5 Teamworking at Ford's Bridgend engine plant

The introduction of teamworking at Ford has not been without its difficulties including a strike in 1988, but a system of teamwork is now in place at the Bridgend Engine Plant and many other factories in the Ford Motor Company. At Bridgend, groups of workers are organised into integrated manufacturing teams (IMT). On the engine assembly lines an IMT is made up of three types of employee:

1. The skilled workers who receive a 5% team allowance.
2. A new grade of worker called an integrated manufacturing specialist (IMS) who are effectively promoted to a higher wage scale.
3. The semi-skilled workers for whom there are no financial incentives to embrace teamwork unless they wish to train for the IMS grade.

The size of an assembly team depends upon the requirements of a particular area, but the number of workers and skill mix are chosen to support all reasonable absence. It is recognised that absence of particular team members might affect the ability of the team to carry out planned maintenance on that day, and that in some cases there may be some borrowing or sharing of workers with particular skills between teams.

The responsibilities of members of an assembly IMT are spelled out in a set of agreements. They include the responsibility of skilled workers to train and guide semi-skilled workers and to be prepared to perform the full range of production functions that may be required to ensure optimum efficiency, uptime and quality.

Typically, integrated manufacturing specialists are given six weeks training resulting in a joint Ford/EITB certificate after which they are expected to perform a range of maintenance functions including fault diagnosis, preventive maintenance checks, replacement of pumps, filters, motors, valves etc., operation of gauging equipment and robot program changes.

Group leaders are selected (i.e. not elected by team members) and they receive special training and an allowance of 10%. Group leaders may be selected from the IMSs or the skilled workers and their function is to assist supervisors with the efficient organisation and running of the section. This might include work scheduling, process control, induction and training of new starters, safety, housekeeping and cover for supervisor absence. Group leaders will not become involved with the grievance procedure, pay determination or negotiations with union representatives.

1.3.6 The Ford 2000 programme

On the first of January 1995, Ford launched a globalisation plan known as Ford 2000 which is believed to be the largest corporate re-engineering effort in history (Ford News, 1998). Under Ford 2000, North American, European, Asian and Latin American automotive operations were consolidated into a single global organisation called Ford Automotive Operations. Ford 2000 is intended to deliver global economies of scale, as well as eliminating duplication and sharing the benefits of initiatives such as the visual factory, the Ford production system (FPS) and Ford total productive maintenance (FTPM).

1.3.7 Ford production system

The scope of the Ford production system is shown by the following figures:

- 148 diverse plants and local governments
- 225,000 manufacturing employees affected
- 1500 - 2000 different processes
- 20 countries and governments
- 42 trade unions
- Over 50 different languages and dialects

1.3.8 Ford total productive maintenance

The Ford Motor Company has adopted a Japanese approach to maintenance through a programme called Ford total productive maintenance (FTPM). FTPM is based closely on Nakajima's (1988) description of TPM and the full benefits will take several years to be realised. The five elements of FTPM are:

1. Conduct preventive maintenance
2. Improve overall equipment effectiveness
3. Use small group activities
4. Training in production and maintenance
5. Early equipment management

1.3.9 Ford today

The Ford Motor Company is the world's second largest producer of cars and trucks. In terms of sales volume, Ford is ranked second on the Fortune 500 list of the largest US industrial corporations. In 1996, Ford's world-wide sales and revenues totalled \$147 billion.

1.4 Background to the Research

The research described in this thesis is set against the background of two distinct trends in maintenance, the increasing use of teamwork and the increasing use of computerised information systems. Both of these trends are the result of an increasing awareness of the importance of good maintenance practice in reducing the costs of manufacturing and improving the performance of manufacturing systems.

1.4.1 Teamwork

The success of manufacturers such as Toyota has encouraged Western industry to examine the Japanese techniques of lean manufacturing which seek to reduce waste. The Japanese have demonstrated the application of these ideas to maintenance in the form of TPM which stresses teamworking, multi-skilling and a blurring of the distinction between maintenance and production (Nakajima, 1988). TPM involves process operators in the maintenance and optimisation of manufacturing processes and in this way leverages their knowledge of each process. Great emphasis is placed both on the collection of data on the performance of processes and analysis of these data to enable improvements to be made. TPM also stresses the importance of visual communication of process information such as set-up procedures, troubleshooting guidelines etc. In many cases, data collection and visual communication is done on paper with managers using simple tools such as spreadsheets to analyse the data.

1.4.2 Computerised maintenance management systems

The second and largely unrelated trend in maintenance is the use of computerised maintenance management systems (CMMS) to manage the maintenance department. Since the early systems were deployed in the late 1970s CMMS have progressed rapidly and powerful user-friendly systems are now available to suit the budgets of most manufacturers (Eason, 1997). These systems allow users to collect, analyse, store and retrieve data on most of their maintenance activities and they are popular with managers for this reason. However, they are written with the needs of the maintenance manager in mind and are often under-utilised by those responsible for carrying out maintenance. Although many CMMS vendors claim that their products are suitable for a TPM environment, their lack of use by production and maintenance personnel undermines such claims. CMMS are also under threat from ERP systems that are claimed to offer the same functions. Despite the advantages of CMMS from a managerial point of view, most popular systems do not adequately support the execution of maintenance where TPM is practised.

1.5 Research Question

The question addressed by this research is how to improve the performance of multi-skilled teams responsible for maintenance and operations in a TPM environment.

This question is addressed by considering the development of maintenance management techniques and maintenance technologies, including CMMS. The research also considers developments in related fields such as other types of information systems that might be applied to maintenance and other approaches to the design and operation of information systems.

Much of the research took place in an automotive engine factory, which features high output automated manufacturing systems in which individual processing stages are tightly integrated. In this environment, effective and timely maintenance is more important than for most discrete component manufacturers. Nevertheless it is felt that this environment represents one extreme along a continuum and that the problems of downtime faced by the engine plant are typical of many lean manufacturers with complex manufacturing systems. The findings are expected to be relevant outside the automotive industry and they have been tested for their applicability to other industries.

1.6 Thesis Structure

In order to investigate the issues raised by the research question, it is necessary to examine the different but related subjects of maintenance, and information systems. Relevant literature on the subject of maintenance is discussed in chapter 2 and a selection of relevant literature on information systems is discussed in chapter 3.

Maintenance is a multi-disciplinary subject and for this reason it is necessary to survey the literature from several inter-related disciplines. Maintenance takes place in many different industrial environments including aircraft maintenance, process plant maintenance and machine maintenance. There are also several different approaches to maintenance such as unplanned and planned maintenance. There were valuable lessons to be learned in different industries and good reasons to look at different types of computer systems such as document management systems and computer-based training systems as part of this project. The organisation of maintenance activities depends upon the nature of the industry concerned. The automotive industry is heavily automated, but rather than diminish the role of human operators this has made them more important than ever in terms of reducing downtime. The reasons for this are covered in the section on automation in chapter 2.

Since the approach taken during this research has been to consider the use of a computer to deliver maintenance information, it is necessary to examine the subject of information systems and their application to maintenance. Chapter 2 covers conventional CMMS but chapter 3 looks at human-centred information systems in general. The reason for considering the human-centred approach is the importance of humans in the TPM approach to maintenance. If a computerised approach is to be used in this environment, it seems reasonable that such an information system should be a human-centred one.

Chapters 2 and 3 therefore constitute the literature review. The conclusions from the literature review are used to formulate the hypothesis that is stated at the beginning of chapter 4. This chapter then continues by describing the research methodology used.

Chapter 5 presents the development of a hypermedia information system in accordance with the methodology described in chapter 4. The evaluation of this information system is described in chapter 6 and the thesis concludes with chapter 7.

1.7 Summary of Chapter

This chapter has outlined the background to the thesis, which is based on research work sponsored by the Ford Motor Company. The scope of the work has been defined as the subject of maintenance, in particular team-based maintenance within manufacturing industry. Today, this usually means TPM.

The chapter has given a brief history of the Ford Motor Company; a history that is described more fully in appendix A. The development of automated manufacturing facilities for engine manufacture has been outlined and the particular requirements of maintenance in this kind of factory have been described. The section on the Ford Motor Company finished by describing the situation today including the Ford 2000 globalisation programme, the use of the Ford production system and its maintenance sub-programme Ford total productive maintenance (FTPM). The implementation of teamworking at Ford has also been described.

Two trends in maintenance have been identified as the increasing use of both teams and information technology. Both trends have been the subject of academic study, and the introductory chapter has suggested that the relationship between these two developments may be problematic.

The question addressed by this research is how to improve the performance of multi-skilled maintenance teams in a TPM environment.

2. Maintenance

2.1 Introduction

This chapter introduces the subject of maintenance, in particular the maintenance of manufacturing systems. Starting with some definitions of maintenance, a brief history of the subject is presented followed by a description of the different types of maintenance activity. As well as describing some of the tools and techniques available to maintainers, the subject of maintenance management is outlined. There is particular emphasis on total productive maintenance since this is the approach adopted by Ford. Lastly the subject of computerised maintenance management systems is described, including conventional systems as well as some more innovative approaches. This is the aspect of maintenance to which the thesis is most relevant.

2.2 Definitions

The British Standard definition of maintenance is given in BS 3811 as "... *the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function.*" (British Standards Institution, 1984) This broad definition applies equally to aircraft maintenance, plant maintenance and building maintenance.

The Department of Trade and Industry offer the following more business centred definition of maintenance: "... *Maintenance is the management, control, execution and quality of those activities which will ensure optimum levels of availability and overall performance of plant are achieved, in order to meet business objectives*". (Department of Trade and Industry, 1991)

2.2.1 Terotechnology

A related concept to maintenance is that of terotechnology, which is a term coined in the UK in 1970. Terotechnology arose from a 1968 investigation into the cost of maintenance in the UK by the then Ministry of Technology (van Rijn and Scholten, 1996). One of the findings of this study was that a likely increase in profitability of 22% could result from a reduction in downtime of only 3% in a typical medium sized company (Husband, 1976).

A committee was set up to address the findings of the report and the result was a new approach called terotechnology which is defined in BS 3811 as "*A combination of management, financial, engineering, and other practices applied to physical assets in pursuit of life-cycle costs. NOTE. Its practice is concerned with the specification and design for reliability and maintainability of plant machinery, equipment, buildings and structures, with their installation, commissioning, operation, maintenance, modification and replacement, and with feedback of information on design, performance and costs.*" (British Standards Institution, 1984).

2.3 Classification of Maintenance Activity

BS 3811 classifies maintenance activities into their various forms using a hierarchy of terminology (Figure 2-1).

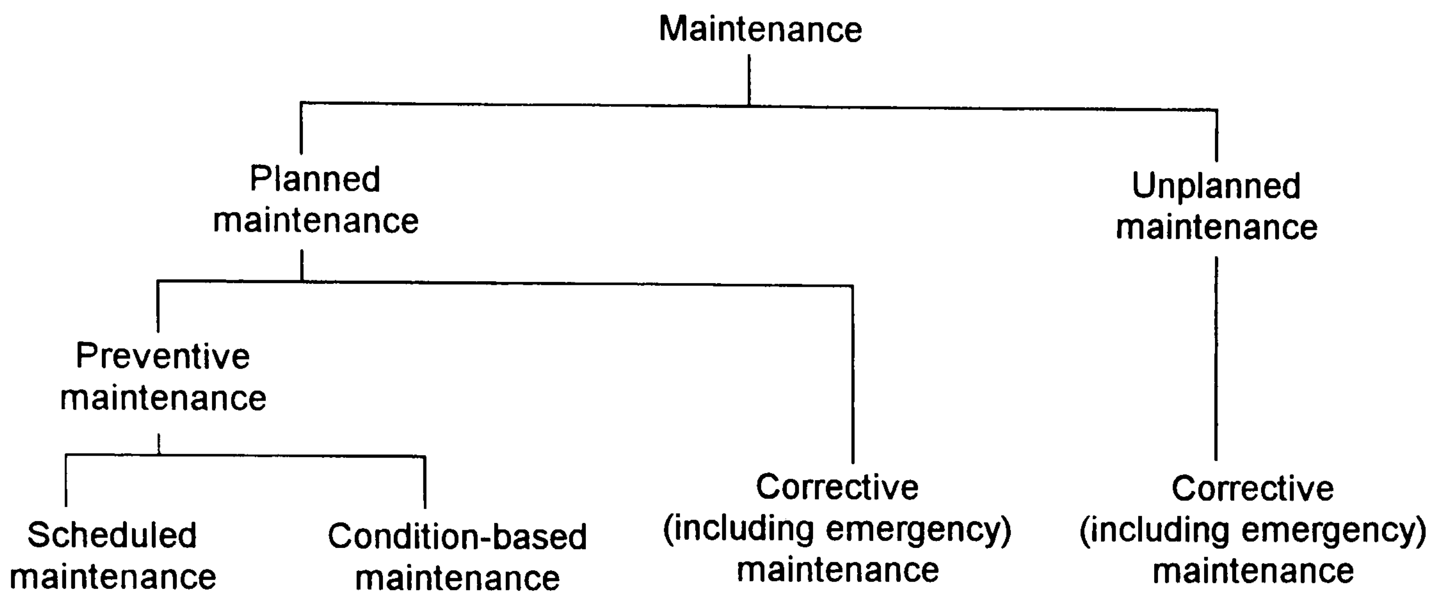


Figure 2-1 Various forms of maintenance (source: BS 3811, 1984)

These terms are related to five different maintenance policies, each of which may be suitable at certain times for particular types of equipment operating in a particular environment. These policies and more are described by van Ek *et al* (1996) and shown in Table 2-1 below:

Maintenance Policy	Description of Policy
Condition-based maintenance (CBM)	CBM refers to maintenance that is carried out based on the analysis of signals from instrumentation used to monitor the condition of an item. There are now many condition monitoring techniques available including relatively simple to operate ones such as thermographic analysis, ultrasonic analysis and more (Niebel, 1994).
Design-out maintenance (DO)	DO seeks to eliminate cyclically recurring failures by component or system to change the failure mode. Much of the cost of maintenance can be saved at the design stage, a fact that is recognised in studies of life-cycle cost (Nakajima, 1988).
Fixed-time maintenance (FTM)	BS 3811 refers to FTM as scheduled maintenance, but some authors refer to FTM as planned maintenance which is felt by van Ek *et al* (1996) to be inaccurate since other equally valid maintenance policies involve planning even where the scheduling of a maintenance task is unplanned.
On-failure maintenance (OFM)	OFM refers to the decision to wait until an item fails (or its performance degrades to a pre-determined level) before initiating maintenance. This is sometime known as breakdown maintenance and although this may be appropriate in some circumstances, savings can often be made by adopting a different policy.
Opportunity maintenance (OM)	OM is maintenance work that is carried out by exploiting an opportunity such as a forced outage, a shut-down period, the availability of excess labour etc. OM may simply refer to cleaning and inspection during such times.
Planned preventive maintenance (PPM)	Many studies refer to planned preventive maintenance, but the BS 3811 term is simply *preventive maintenance* which can then be divided into two of the above policies namely FTM and CBM. For this reason, PPM is not regarded as a distinct maintenance policy.

Table 2-1 Maintenance policies (source: van Ek *et al*, 1996)

2.4 History of Maintenance

It is necessary to look firstly at maintenance in the broadest sense for two reasons:

1. Maintenance is closely related to the concepts of quality and reliability and there is much valuable work in these three areas that is not directly concerned with manufacturing systems.
2. Many of the analytical and organisational techniques developed in the fields of quality, maintainability and reliability since the 1940s have been and are being applied to manufacturing.

A useful history of Reliability, Availability, Maintenance and Safety (RAMS) is given by van Rijn and Scholten (1996). They show that significant developments in RAMS were driven by the requirements for effective weapon systems, more cost effective aircraft maintenance, safer process industries including nuclear power stations and product liability laws. Manufacturing industry has benefited only relatively recently from these developments, and then this has been led by the Japanese. This history of maintenance is shown in Table 2-2 below:

Era	Location	Goal	Technique	Champions
40s	World War 2 Germany	Solve unreliability of V-1.	Weakest link concept.	Lusser
	USA	Missiles reliability. Improvement in design.	Quality control. Sampling and acceptance testing.	Deming
50s	USA military	Korean war, improve availability and reduce cost of maintenance.	The AGREE report. Integral activities in the development cycle. Component testing.	Dept of Defence
	Nuclear weapon systems	Understand and correct human errors.	Compilation.	Sandia Laboratories
60s	USA commercial airlines (Boeing 747)	Maintenance evaluation and program development, MSG-1.	Decision-diagram technique.	United Airlines Nowlan
	USA missile programme (ICBM, Mercury, Gemini)	"Demand for success".	Component testing. Reliability block diagrams.	Watson, Haasi
end 60s	US maths departments	Reliability engineering mathematics.	Fault tree analysis, Mil. Standards.	Birnbaum, Barlow, Proschan
70s	UK Ministry of Technology	Management (financial, engineering) of physical assets.	Terotechnology.	
	USA nuclear industry	Quantified Risk Assessment, WASH 1400.	Fault tree analysis.	Rasmussen
	Europe	Industrial hazards, (Rijnmond, Flixborough, Seveso).	Risk studies, HAZOP, QRA, consequence modelling.	Dutch Ministry of Environment, ICI
80s	USA chem. Industry	Industrial safety.	Standards.	OSHA
	USA defence	Product liability. Cost-benefit reliability/ maintenance.	R&M 2000.	
	Japan	System availability.	Total productive maintenance, TPM ("Q circles").	JIPE, Nakajima
90s	USA	Operational safety, the 'maintenance rule'.	Assessors and workers share plant information (IT).	NUREG
	Japan	Quantitative support of TPM.	Process/equipment models on-line.	
	Europe	Machinery Directive.	Basic information on equipment safety aspects.	European Commission
		Maintenance and availability of plant.	RCM.	Large-scale industry, consultants

Table 2-2 The Evolution of RAMS (source: van Rijn and Scholten, 1996)

2.4.1 The development of early maintenance techniques

Van Rijn and Scholten identify the origins of RAMS as the 1940s when both the Germans and the Americans were experiencing failures in the first generation of guided missiles. Rules for the reliability of series systems were developed that showed that the system reliability was significantly less than that of its weakest component. The Americans used Deming's new theories of quality control to improve their weapons by designing out their unreliability. The Americans developed these techniques further during the Korean War. Statisticians were used to develop design and analysis techniques that eventually became the subject of military specifications, such as fault tree analysis and failure modes and effects analysis. The 1960s saw the beginning of reliability engineering as a distinct scientific discipline.

2.4.2 Aircraft maintenance

As well as technological and mathematical approaches, the 1960s saw the development of management tools to improve reliability. The US Federal Aviation Agency had noticed that airlines were not able to significantly reduce the failure rates for certain types of engines by changing their overhaul policies. United Airlines studied a range of non-structural aircraft components and systems and concluded that only a small proportion of components (4%) conformed to the assumed 'bathtub' curve for age related failures. The majority (68%) in fact had an 'infant mortality' phase followed by a period of constant failure rate with no wear out phase. These findings led United Airlines to design an approach to maintenance that took account of the different age-related failure patterns they had discovered. The approach to aircraft maintenance became standardised as MSG-1 and led to the development of reliability-centred maintenance (RCM). More recently aircraft maintainers have demonstrated the use of digital technology to reduce the costs of maintenance documentation. Interactive electronic technical manuals (IETMs) are supplied with the latest aircraft such as the Boeing 777 and are developed by some maintainers such as British Airways Maintenance Cardiff. Appendix B describes the use of such information by BAMC. The US Department of Defense promotes the use of IETMs as part of its continuous acquisition and life-cycle support (CALS) programme, which is described more fully in paragraph 3.15.

2.4.3 Life-cycle costs

The importance of cost control over the life-cycle of a product or process is better understood now than it was in the 1970s, when the promotion of terotechnology failed to galvanise UK industry. The goal of economic life-cycle costs is effectively the same as the aim of TPM, which is to maximise equipment effectiveness (Nakajima, 1988). Now that the Japanese have demonstrated the benefits of the minimisation of life-cycle cost through TPM, it is ironic that the West is now realising the importance of this approach, twenty years later. TPM and RCM programmes are now common in Western industries, especially automotive manufacturers such as General Motors (Hamrick, 1994), Rover (Yeomans and Millington, 1997) and Ford (Owen, 1994).

2.5 Maintenance in Manufacturing

The importance of reliability and maintenance has long been understood by aircraft operators and by the military in general. However, it is only relatively recently that the reduction of life-cycle costs through maintenance has received close attention from manufacturing managers.

2.5.1 Cost of maintenance

The 1968 study by the UK Ministry of Technology reported that the overall cost of direct maintenance in the UK was £1.1 billion. More impressive was the belief expressed in the report that these costs could be reduced by 40% if maintenance staff productivity could be improved, which would also save £300 million in lost production (van Rijn and Scholten, 1996).

In 1991 the DTI carried out another survey which showed that UK industry spent £14 billion annually on maintenance of equipment worth £80 billion. At the same time, annual spend on new equipment was £4.3 billion (Bates, 1996). There is evidence however, that relatively modest expenditure on maintenance can yield significant savings. A capital equipment manufacturer quotes a saving of £1 million over two years from an investment in maintenance of £100K (Department of Trade and Industry, 1991).

In manufacturing industry maintenance has suffered historically from poor status. This can be blamed on a poor understanding of the strategic importance of maintenance in the boardroom, which stems from a misunderstanding of the true cost of ineffective maintenance (Nayak and Shayan, 1995). The cost of maintenance is often calculated as the cost of maintenance labour and materials without including the cost of lost production through downtime. The cost of lost production is usually approximately 4 times as high as the cost of maintenance, but it may be as much as 15 times as high (Wireman, 1990). It is estimated that in the next several years, the annual cost of maintenance will exceed the annual spend on new capital investment (Nayak and Shayan, 1995).

2.5.2 The cost of maintenance in different industries

Although many of today's maintenance techniques originated in the aerospace industry, the cost of maintenance in non-aerospace discrete component manufacture is far lower, with continuous process industries somewhere between the two. A survey by Booz Allen and Hamilton for The Economist Intelligence Unit (Wittemann and Peschl, 1993) shows how these costs compare (Figure 2-2).

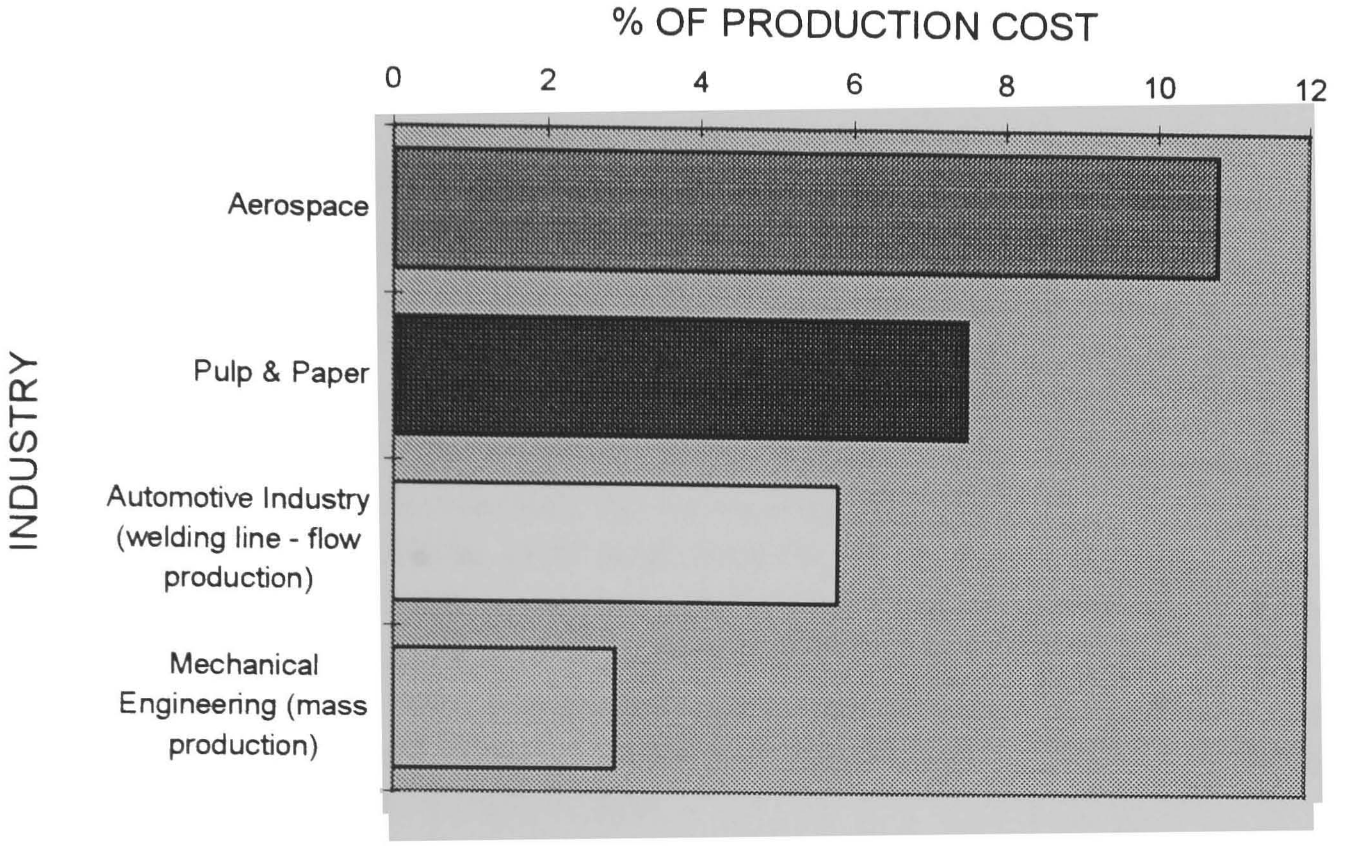


Figure 2-2 Maintenance Cost Comparison (after Wittemann and Peschl, 1993)

2.5.3 Trends in maintenance management

Luxhøj *et al* (1997) describe how many manufacturing organisations are now realising the critical need for effective maintenance of production facilities. In a benchmarking study of Scandinavian and US manufacturers, they identify two major trends in maintenance management. These are:

1. The emergence of advanced maintenance technologies and methods, such as expert systems and condition monitoring.
2. The linking of maintenance to quality improvement strategies and the use of maintenance as a competitive strategy.

2.6 Maintenance of Complex Automated Systems

The cost of downtime can be particularly high for complex manufacturing systems such as flexible manufacturing systems (FMS) and automated transfer lines such as those in Ford's engine plants. The annual downtime for a computer numerical control (CNC) machine tool might typically cost $50,000 and it is not uncommon to find downtime figures of 30-40 percent for FMS (Somers and Gupta, 1991). The causes of such high downtime might be explained by the complex and highly integrated nature of FMS, which are designed for high output and low work-in-progress. Such complexity can also make these systems vulnerable to any failure of individual components or sub-systems.

A good example of such breakdowns is given by Shaiken (1989) in a study of an FMS comprising 12 CNC machine tools supported by a material handling system, which produced transmission casings. Even the supplier of the FMS estimated that downtime might be as high as 33%.

2.6.1 Transfer lines and reliability

Automated transfer lines use similar technology to FMS and can have even higher levels of output, but they can also be more vulnerable to unreliability (De Garmo *et al*, 1988). A transfer machine is a group of single or multi-spindle machine tools arranged in a linear or radial fashion around an automatic material handling device so that material is processed in a set of sequential steps with no human intervention. When each machine tool has finished its cycle, the handling device indexes all material to the next process. Each process must have a similar cycle time since the slowest process dictates the speed of the machine, and any processes that are significantly faster must wait until the other processes have ended their cycles. It is important that each process be reliable and well supplied with cutting tools since a stoppage on any one process will stop the entire machine. When an automated material handling system is used to join two or more transfer machines, they form a transfer *line*.

Transfer lines are used to manufacture discrete components in high volume, typical products being automotive engines. Just as transfer machines are vulnerable to components or system unreliability, the more closely integrated transfer lines are even more vulnerable. Whereas an FMS uses a supervisory computer to calculate schedules and manage the flow of material, an automated transfer line moves material uni-directionally through a more rigidly defined sequence of processes. Transfer lines are therefore inherently less flexible than FMS but they are capable of higher output and they are far simpler to schedule.

The vulnerability of transfer lines to failure of any individual machine can be reduced by introducing buffer stocks of material around certain machines which has the effect of de-coupling the processes. In the event of a process failure the buffer following that machine can feed the downstream part of the line and the buffer before the machine can take material from the upstream part of the line. These buffers are usually in the form of sections of conveyor whose length is calculated to hold the required amount of stock (Figure 2-3).

If the downstream buffer empties, then the downstream part of the line will become *starved* and if the upstream buffer fills up then the upstream part of the line will become *blocked*. It is important for maintenance workers to ensure that the failed process is restored before either starvation or blockage occurs. It is also important to estimate accurately the likelihood of failure of each process to determine the optimum sizes of inter-process buffers. Whilst they should be as small as possible (ideally zero) to minimise work-in-progress (WIP), they must be sized to optimise system output.

Computerised simulation tools are used extensively in the design of transfer lines, but they will only deliver useful results if accurate estimates of process reliability are used (Somers and Gupta, 1991).

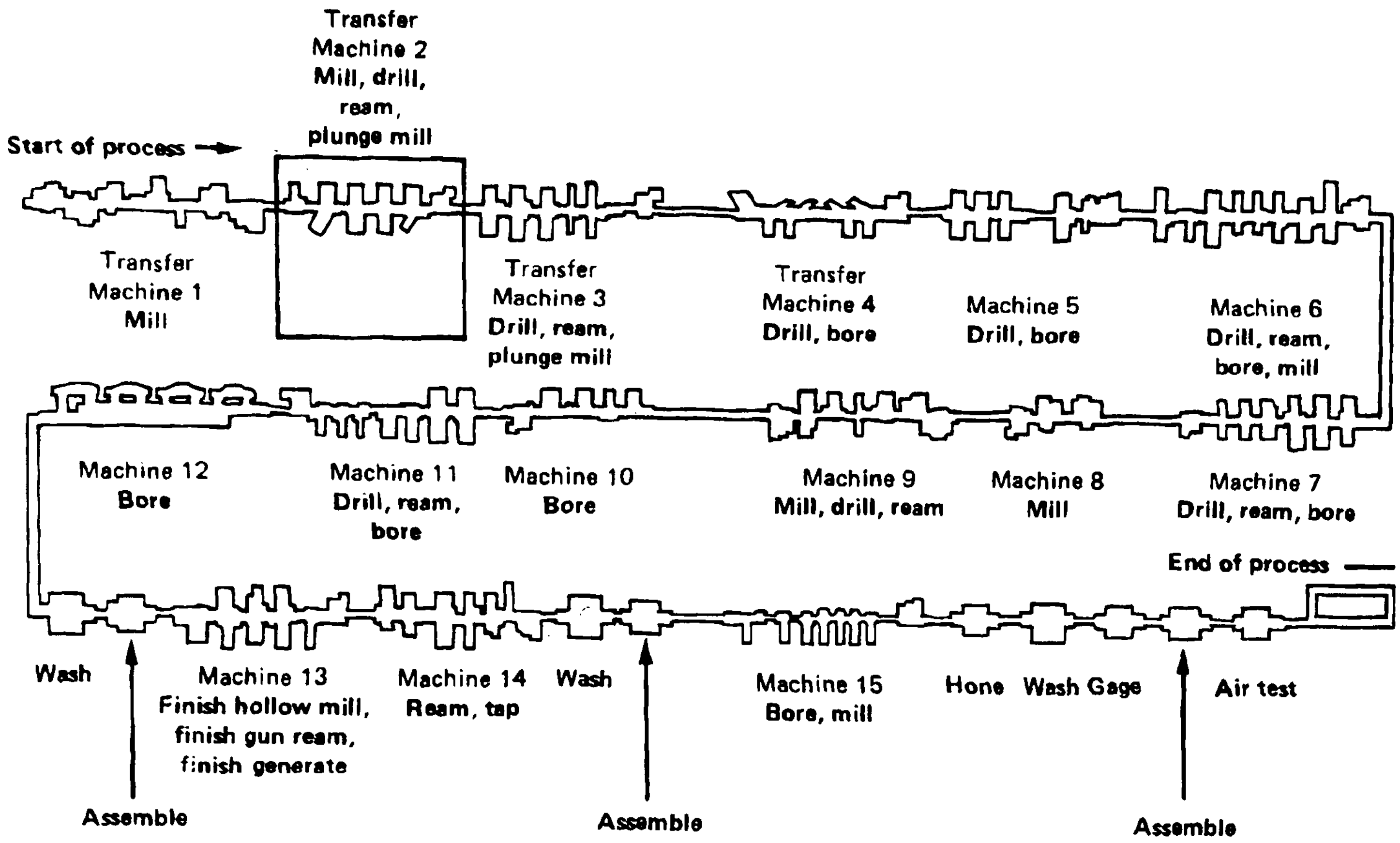


Figure 2-3 Ford machining line (Source: Mason,1985)

2.6.2 Maintenance of early transfer lines

Although the first use of transfer machines in automotive manufacturing was in the UK at Morris Engines Ltd, the machinery was unreliable and too complex (Woollard, 1954). It was the Ford Motor Company who pioneered the large-scale use of such systems in the Cleveland Engine Plant, which opened in 1952. The man who championed the use of such technology (and claimed to have coined the term *automation*) was Delmar Harder, the vice president of manufacturing at Ford. Harder understood well the vulnerability of transfer lines to breakdowns, but he argued that sound design of transfer machines, the application of planned maintenance principles and the development of plant workers through extra training would allow automated transfer lines to deliver increased output and quality without excessive downtime (Harder, 1954). Appendix A describes how, despite the development of several innovative approaches to maintenance at the Cleveland Engine Plant, downtime remained a problem.

2.6.3 Maintenance information at the Cleveland Engine Plant

In an early edition of *Automation*, R.N. Johnson of the W.F. & John Barnes Company who supplied the Ford Motor Company with machine tools writes about electrical maintenance (Johnson, 1954). The difference between automated machine tools and older designs was the addition of hydraulic, pneumatic and electrical systems to the older mechanical devices. Johnson argues that this places maintenance personnel in a dominant position in the production plant, yet machine tool designers have generally focused on ease of operation and output with maintenance being secondary. Unless machine designers give maintenance a higher priority, unskilled and semi-skilled workers who have been displaced by automation will have to be replaced by equal numbers of highly trained service technicians.

Of particular interest is the emphasis Johnson places on usable information. He argues that more information should be made available to the customer's maintenance personnel and that it should be in their hands instead of a file in the office. He recommends Barnes' customers to encourage their maintenance and operating personnel to steal control drawings from their machines. In Johnson's view, this is a healthy sign of interest in machine operation. He describes how Barnes makes its customer's maintenance personnel familiar with machine operation through:

1. Personal interviews between Barnes engineers and customer production and maintenance engineers before and during design and after installation of a machine.
2. Introduction of mechanical trouble finders on machinery to help maintenance personnel to diagnose problems quickly.
3. Use of customer's maintenance personnel in installation of machines.
4. Presentation of complete information on the controls of the machine which consists of:
    - Schematic line drawings.
    - Machine equipment layouts.
    - Complete equipment parts lists and recommended maintenance stock list.
    - Step-by-step description both in simple graphic form and in writing of the mechanical sequence of operations of the machine.
    - Step-by-step description in written form of the electrical sequence of machine operation.
    - Inclusion of all this into a standard binding.

Whether the presentation of information in this format was ever achieved is not recorded, but modern microcomputers make such an information system possible. The use of digital networks facilitates the cost-effective maintenance of the information.

2.7 Maintenance Management Activities

The principal maintenance problems identified by Wireman (1990) in a benchmarking study were schedule conflicts, hiring and training of personnel, breakdowns, excessive inventories, lack of management support and budget control.

These could be regarded as management problems as distinct from technological problems. As has been described earlier, there are several different maintenance policies that could be adopted in particular situations, but maintenance management has traditionally been seen to consist of three components:

1. Maintenance functions
2. Maintenance policy and maintenance work
3. Cost reporting

To these three can now be added a fourth function of maintenance quality control. These components are managed using familiar techniques such as project management, work measurement, scheduling, inventory control, quality control and training (Raouf *et al*, 1993; Raouf, 1994). The way in which these techniques and associated activities support the maintenance process is shown in Figure 2-4.

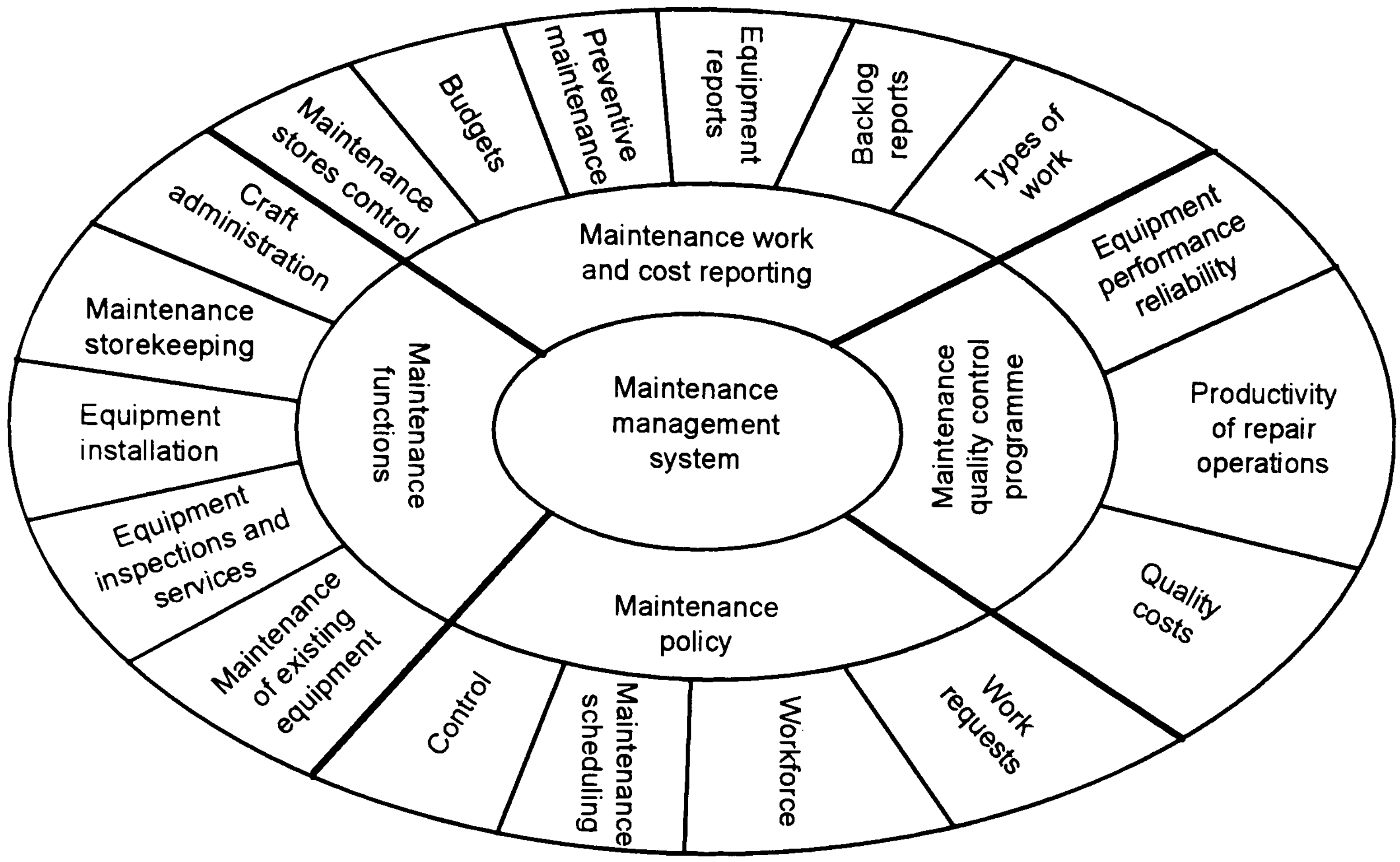


Figure 2-4 Typical maintenance management activities (source: Raouf *et al*, 1993)

2.7.1 The human factor

A study of manufacturing systems maintenance must include a study of the man-machine interface at least until it becomes possible to automate the entire maintenance process. According to Kahen (1997), humans cannot be removed from an automated manufacturing system since manufacturing technology involves four major interrelated elements. These are:

1. Technoware: Object-embodied technology or technical components.
2. Humanware: Person-embodied technology (human skill and activity).
3. Infoware: Document-embodied technology (documentary knowledge-based technology) or information components.
4. Orgaware: Institution-embodied technology (all aspects of management activities, organisational structuring, communications and networking)

These four elements interact with each other to create a micro-environment. Technology within the micro-environment facilitates interaction between the micro-environment and the macro-environment to effect productivity improvement. Kahen considers that the human element dominates the interactions within the whole system and argues for a more human-centred approach to manufacturing systems since "without manpower adjustment and participation the tremendous potential of advanced technologies cannot be realised". Kahen examines four key related strategies that are common in modern manufacturing; total quality control, just-in-time, flexible automation and total productive maintenance. He argues that in each case, the human element is of central importance and illustrates this in Figure 2-5.

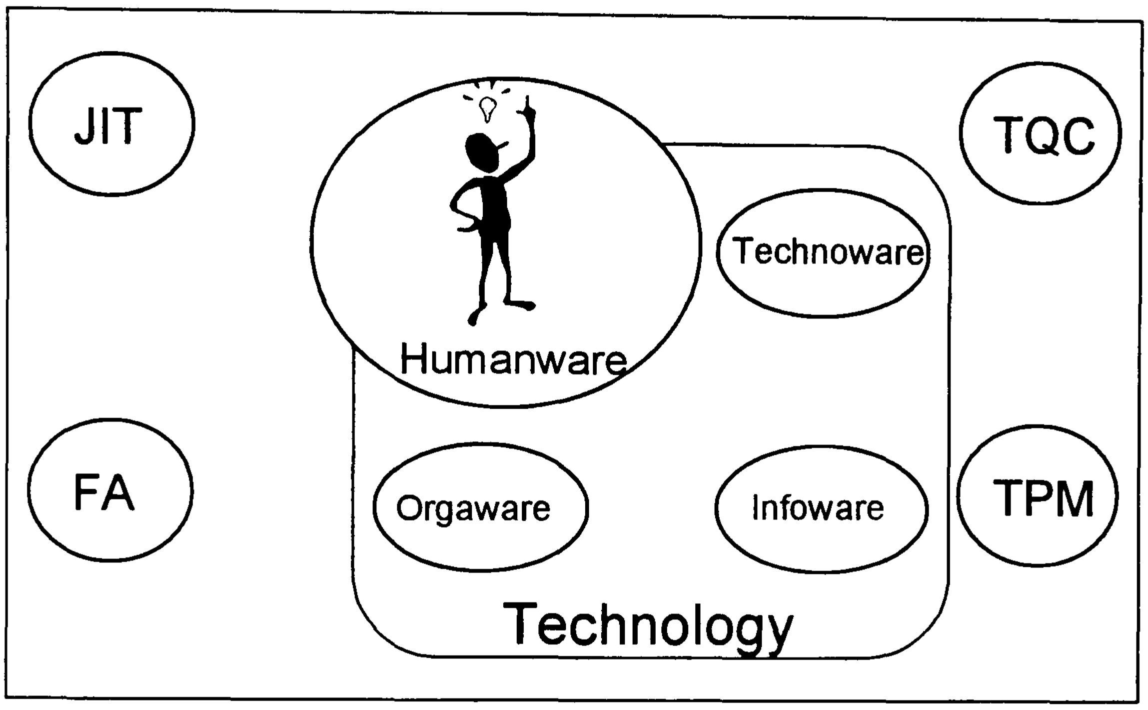


Figure 2-5 AMT and the situation of Humanware within four manufacturing strategies (source: Kahen, 1997).

In the case of flexible automation, Kahen makes the point that although such technology has dramatically reduced the number of workers in such manufacturing systems, it has put the human in a more critical role than ever as a unique source of intelligence within the complex system.

It is now commonly accepted that in automotive manufacturing, close attention must be paid to the human factor in order to achieve high output of high quality products at low cost. Automotive manufacturers have abandoned the rigidly demarcated mechanistic approach which has become known as *Taylorism* or *Fordism* in favour of Japanese lean manufacturing techniques (Womack *et al*, 1990). Lean manufacturing companies use a range of methods of reducing waste in manufacturing, one of which is to enlist the expertise of workers through continual improvement programmes known as *kaizen*.

In their study of *New Wave Manufacturing* (NWM), which is a term coined to cover the related concepts of lean manufacturing, just-in-time, world-class manufacturing and total quality management; Harrison and Storey (1996) describe the need to consider social and organisational issues as well as technical and operational issues. Referring to a study by Wilkinson and Oliver (1989), they state that:

> "Companies which continue to adopt NWM systems without addressing its social and political implications will lay themselves open to the disruption experienced by Ford in early 1988".

According to Wilkinson and Oliver, this is due to the *pervasiveness* of disruptions to production within a manufacturing organisation, the *immediacy* with which disruptions are felt by the organisation and the *substitutability* of the workers in the manufacturing system. Just-in-time manufacturing is vulnerable to disruptions such as industrial action, as well as breakdowns, which illustrates the importance of good industrial relations and worker satisfaction in such industries. The importance of supporting new technologies with changes in organisational approaches is emphasised by Helfgott (1987) who quotes Hirschhorn thus:

> "The new cybernetic machines create new sources of error and failure with which only skilled workers, ready to learn and adapt to the new production conditions can contend".

Helfgott also mentions a study of the US electrical machinery industry by NEDO in the UK that concluded that without new organisational approaches, at least 40% of the realisable benefits of programmable automation would be lost. Helfgott describes ways in which some companies are changing, including increasing the skills of production workers and creating new categories of job such as the operator/maintenance function. Today's reader will recognise this as TPM.

2.8 Total Productive Maintenance

TPM is an approach to maintenance developed by Seiichi Nakajima who was the Vice President of the Japanese Institute of Plant Maintenance (JIPM). Nakajima introduced TPM in Japan in 1971 and he published the English translation of *Introduction to TPM* in 1988 (Nakajima, 1988).

TPM has been particularly popular in the automotive industry and in the years between 1971 and 1988, sixty percent of the winners of the Japanese prize for successful implementation of TPM were Toyota group companies. Indeed the first application of TPM was at Nippondenso, a Toyota Group company (Womack and Jones, 1996). This demonstrates the close relationship between just-in-time production and TPM and explains why the Ford Motor Company has incorporated TPM into the Ford production system.

2.8.1 Important features

The two goals of TPM are zero breakdowns and zero defects and the most important features of TPM are:

1. Activities to maximise equipment effectiveness
2. Autonomous maintenance by operators, and
3. Company-led small group activities

The first of these features includes the use of a unique performance measure known as overall equipment effectiveness (OEE). This is expressed as a percentage and it allows a manager to measure the performance not only of the maintenance function, but also the operation of the equipment and the quality of the products being produced. OEE is therefore a measure of *total* productivity, which is necessary for TPM since this approach involves many more areas of the organisation than a traditional maintenance department.

The second feature is also unique to TPM and it is often one of the most difficult changes to introduce. It involves a major change in the culture of many manufacturing organisations from "I operate - you fix" to one of co-operation and work sharing between operations and maintenance.

The third feature is not unique to TPM, since it is found in many improvement programmes such as kaizen (Imai, 1986). It is however essential for the success of TPM and further illustrates the interaction between TPM and other Japanese inspired production philosophies.

2.8.2 The five TPM developmental activities

According to Nakajima (1988), it takes about three years of TPM implementation before an organisation will see prize winning results and the implementation plan will be different in each case. He lists five basic developmental activities that should be followed:

1. Elimination of the 'six big losses' to improve OEE
2. An autonomous maintenance programme
3. A scheduled maintenance programme for the maintenance department
4. Increased skills of operations and maintenance personnel
5. An initial equipment management programme

The first and second of these activities involve concepts unique to TPM.

2.8.3 Autonomous maintenance

Autonomous maintenance does not mean the elimination of the maintenance department. Instead maintenance personnel should assist production workers to become more autonomous and help to develop maintenance standards. Maintenance and production will actually work more closely together and since operators will be organised into teams, there may be maintenance personnel assigned to the teams.

Nakajima recommends that the transition to autonomous maintenance be carried out in seven steps which are related to the '5 Ss' of Japanese-style operations management: *seiri* (straighten up), *seiton* (put things in order), *seiso* (clean up), *seiketsu*, (personal cleanliness) and *shitsuke* (discipline). Imai (1986) provides the English translations.

The seven steps to autonomous maintenance require that information be made available to the operators in the form of standards and information about the function and care of their machines. The hypermedia information system described later in this thesis contains this type of information as it is intended to empower operators to carry out autonomous maintenance.

2.8.4 Small group activities

The third important feature of TPM is the use of small group activities. This is not unique to TPM but here the purpose of the small group activities is to promote autonomous maintenance by operators. TPM small group activities are similar to those developed by the US zero defects movement. This is more formalised and management-directed than the quality circles model (Nakajima, 1988).

2.8.5 TPM in the West

In a two-year benchmarking study of four Japanese transplant companies operating in the US Midwest, Chen (1994) studied maintenance practices and the contribution of maintenance to quality and productivity. The four companies enjoyed high levels of availability (OEE figures are not given) including an average of 80% for an engine plant using transfer lines.

One important finding was that this high availability was not due to any one maintenance practice but a range of common factors. All four companies enlisted their operators for preventative maintenance tasks including cleaning, reading of oil levels, meter readings etc. In some cases, operators were used to assist maintenance staff with strip downs and simple repairs. All four companies kept extensive records of their maintenance activities including records of maintenance schedules, downtime causes and trends, repair histories, the results of lubricant analysis and failed and replaced parts. Computers were widely used for record keeping, data analysis and the accumulation of a maintenance knowledge base, but only one of the firms actually used a commercial CMMS.

2.8.6 TPM and computers

Yeomans and Millington (1997) describe how Rover Group uses computer systems to support TPM and a separate CMMS to support the maintenance department. The CMMS is used to monitor costs, control spares inventory and schedule planned preventive maintenance. The TPM system is used purely for data gathering and information processing.

The Japanese approach to continuous improvement seems to rely much less on computers than the Western approach. An example of an award winning Japanese TPM user is the Nachi-Fujikoshi Corporation. This organisation places a typically strong emphasis on training and makes extensive use of paper for data collection, activity records, checklists and standard procedures. The activities of TPM improvement circles are displayed on bulletin boards as a visual record of their progress towards zero downtime and zero defects. There is no mention however of the use of any computer to make this information available to operators or to allow them to input their data (The Nachi-Fujikoshi Corporation and the JIPM, 1990).

2.9 Why Use a Computer for Maintenance?

Whether maintenance is carried out by skilled technicians or operators it will involve the generation and use of large amounts of information. Examples of this information are the planned maintenance schedule, the list of daily, weekly and monthly checks, the part numbers and stores locations of spares, fault histories, downtime data and the work instructions for maintenance tasks. With the availability of ever more powerful and cheaper processing power, the potential benefits of the application of computers to maintenance seem clear for all but the smallest organisations. Maintenance management software has been available since the late 1970s (Eason, 1997) and is now common in manufacturing industry.

However in studies of CMMS by Raouf *et al* (1993) and of maintenance management information systems (MMIS) by Hipkin (1997), there is evidence that such systems have often failed to deliver expected benefits. According to Raouf *et al* (1993), the reason why such systems often fail is that they are designed by people with insufficient experience of maintenance management. Hipkin (1997) describes how maintenance management software now includes more than simply planning and scheduling. Today's software tools may feature expert systems and some systems are claimed to support maintenance strategies such as RCM and TPM.

2.9.1 The CMMS industry

In 1995, a study by Automation Research Corporation stated that total revenues for maintenance software were over $553 million, with the USA representing 61% of the global market. The study estimated that revenues would exceed $1 billion in 1998. The president of PSDI, (leading CMMS vendors) feels that one of the reasons for such growth is the change in perception of the maintenance organisation. He states that "Companies have changed maintenance operations from an expense centre to a profit centre by reducing costs through optimised maintenance practices" (Manji, 1996).

Another reason for the rapid growth, according to the Automation Research Corporation report, is that advances in information technology now allow vendors to present scalable open solutions which range from stand-alone PC applications to large multi-site enterprise wide environments built around client/server technology (Manji, 1996).

2.9.2 Types of maintenance management software

Most studies of the use of maintenance management software refer either to CMMS or maintenance management information systems (MMIS). CMMS usually refers to the more traditional design of software, typical of early systems, which is used by maintenance managers to plan and control the work of the maintenance department and to monitor costs. The functions of this type of system have been outlined by Niebel (1994) as follows:

1. Equipment control - through the use of a database called an asset register which details equipment specification, location, maintenance procedures, repair history etc.
2. Work control - through the use of another database which controls the flow of work orders describing the tasks to be performed by members of the maintenance department, and which logs the work carried out with associated costs.
3. Maintenance spare parts and inventory control - through a third database of spare part descriptions, costs, locations, stock levels and usage histories.
4. Cost accumulation and reporting
5. Performance reporting

An accurate figure for maintenance cost can help managers to make informed asset replacement decisions, but a CMMS can only provide accurate figures if system users input the data. The core of most modern CMMS is a relational database and the functions of the three databases described above are provided by relations between the data (Eason, 1997). CMMS can generate a wide range of standard and customised reports by querying the data according to the requirements of any maintenance organisation. Examples of such reports might be the plant availability report, the hours spent by certain trades, an analysis of downtime by cause and equipment type, the hours spent against certain items of plant or the average response time.

2.9.3 Functional modules of a typical CMMS

The functions outlined above are often realised by separate software modules that are integrated to constitute the CMMS. The relationships between the modules and functions of a typical CMMS are shown in Figure 2-6.

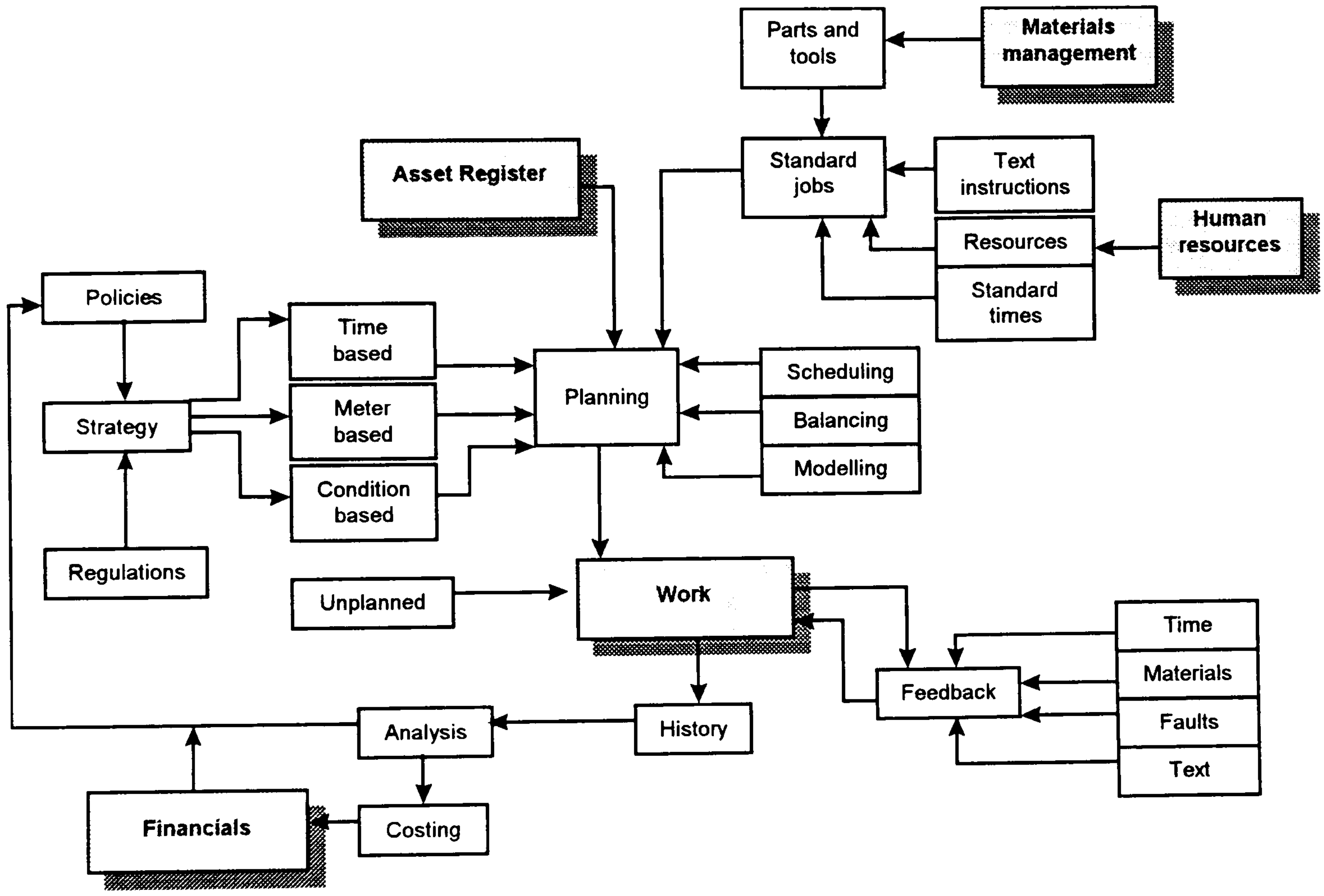


Figure 2-6 Maintenance work management system (source: Kelly, 1997)

2.9.4 Integration

The term 'maintenance management information system' usually refers to an extended information system that incorporates the above functions with the addition of extra information and data input screens necessary to support programmes such as TPM and RCM. Many MMIS vendors sell the ability to integrate their systems with other information systems used by their customers such as MRPII and Enterprise Resource Planning (ERP) systems. The reason for doing so is not only to allow maintenance performance to be reported into wider company systems, but also to allow maintenance activities to be scheduled at the same time as production (Lawrence, 1997).

Several organisations use condition-monitoring equipment with associated data analysis software to carry out preventive and predictive maintenance. It is likely that the maintenance department of the future will have a completely integrated maintenance database, including records of the condition of assets as measured by monitoring techniques such as thermography, ultrasonic testing and metal thickness testing (Valenti, 1991). This has been common in aircraft maintenance for many years.

2.9.5 Evaluation of maintenance management information systems

There has been little research into the introduction and use of maintenance management information systems, but one study looked at five organisations that had implemented maintenance information systems. Managers, supervisors and operators were interviewed to compare their beliefs about the relative importance of postulated success factors both before and after the implementation of their MMIS. The findings confirm the view that process knowledge is accumulated through experience, problem solving and trouble shooting but that this knowledge is rarely made explicit. The MMIS implementation process was also found to have imposed a discipline on the organisations, which played a key role in acquiring and formalising knowledge. In general, the five organisations could not identify any direct <u>technical</u> benefits of MMIS, but they could point to many examples of unexpected non-technical benefits such as increased process knowledge, improved discipline and procedures and enhanced communication and teamwork (Hipkin, 1997).

These results are echoed in an analysis of 725 maintenance management audits carried out on behalf of the DTI in the UK. This shows that over 60% of companies are not satisfied with their MMIS. One reason for this is the absence of a clear maintenance strategy in 85% of the companies audited. If there is such a strategy, this should be supported by the CMMS used. Another reason for user dissatisfaction is the lack of attention paid to the people issues of information systems. Examples are insufficient or ineffective training and a failure to address the fear among some users of the QWERTY keyboard (Jones, 1994).

A common criticism of conventional MMIS is that they do not allow effective access to information for the maintenance technicians themselves. In some cases this may be because paper-based maintenance systems and many computer-based systems do not allow effective access to information. The information may be fragmented and may exist across many different media, which makes access difficult (van Ek *et al*, 1996). It may be that the shop-floor environment requires fundamentally different methods of information presentation and data collection than the office environment for which most CMMS seem to be designed. Developments in multimedia information systems, portable computers and novel user-interfaces may be particularly relevant to maintenance activities (Wilson, 1996).

2.9.6 Who uses CMMS in practice?

In a postal survey of maintenance practices at 231 metalworking plants in the US, Swanson (1997) found that 60% were using CMMS. These respondents were asked to consider eleven modules commonly found in such systems, and were asked which of these modules were present in their systems and how frequently each module was used. The results confirm that the most common use for CMMS is in the planning and scheduling of preventive maintenance work. This module and that for recording the repair history are the most common modules in the systems belonging to the users surveyed. Swanson also asked respondents who the main users of their CMMS were. The results are shown in Table 2-3.

Personnel	**Percentage use by certain personnel**	**Extent of use** 1 = rarely 5 = frequently
Maintenance supervisors	93.2%	3.9
Maintenance planners	86.1%	4.0
Maintenance craftsmen	86.1%	2.9
Purchasing personnel	77.9%	3.3
Store room personnel	64.7%	3.6
Production supervisors	51.9%	2.3
Production operators	36.8%	1.8

Table 2-3 Plant CMMS users (source: Swanson, 1997)

The most striking result from Table 2-3 is the relatively infrequent use of CMMS by those personnel responsible for carrying out maintenance tasks. This suggests that although CMMS are widely used as planning tools by managers, they are least likely to be used to support communication, analysis and co-ordination. Swanson points out that some systems allow production workers to enter work orders directly which improves reporting accuracy and reduces response time. She also feels that while existing means of communication such as e-mail, telephone and face-to-face communication might be adequate in some situations, there are situations where a well designed CMMS might be a more appropriate means of enhancing the flow of information between maintenance and production staff.

2.10 Novel Uses of Computers in Maintenance

Although most commercial CMMS and MMIS have similar functions to each other and can be illustrated by Figure 2-6, there are several alternative ways in which computers have been used to support maintenance.

2.10.1 The use of MRPII for maintenance

Just as some organisations are integrating their CMMS with their factory systems and ERP vendors are keen to point out how effectively their products can be used to manage the maintenance function, some researchers feel that the MRPII logic can be adapted to meet the requirements of maintenance. In a book describing a research project, Shenoy and Bhadury (1998) argue that since MRPII is used for the planning and control of the manufacture of dependent demand items, it can also be used to plan and control maintenance activities which are dependent on the condition of plant. They recognise the following limitations of MRPII in this role:

1. Not all maintenance tasks exhibit demand that is known in advance - MRP can only be used for planned maintenance tasks.
2. Traditional MRP does not schedule manpower, which must therefore be treated as an inventory item.
3. MRP plans the purchase of items which are assumed to be fit for use on arrival, and does so according to fixed lead-time assumptions. Maintenance tasks exhibit more variability in quality and timing.

However Shenoy and Bhadury (1998) explain how these limitations can be accommodated by modifications to the MRPII logic and they describe its application in a power plant. Their system is designed for three types of user - administration, top management and middle management and they make no mention of teamworking or TPM. Although they briefly describe a decision support system that is associated with their planning tool, they do not mention the requirement for rapid access to maintenance information such as drawings, circuit diagrams, spare part specifications etc.

The main reason why such a system is attractive is that most manufacturers own an MRPII system or an ERP system anyway. If these systems can be used to manage maintenance without the purchase of a specialist CMMS, then the cost of the CMMS, its support and its integration with business systems can be saved. The parallel scheduling of production and maintenance is often difficult for manufacturers (Paz and Leigh, 1994) and using a single information system for both types of scheduling has obvious attractions.

Writing from the point of view of a CMMS vendor, Mulcahy (1999) responds to the threat to CMMS from ERP. He claims that the specialist nature of CMMS makes such software more suitable for maintenance management than more generic business systems like ERP. He describes a three-tier model for future CMMS development, in which the data and business tiers are generic, but the user tiers are highly configurable. He claims that this model will allow easier integration with business systems whilst giving maintenance departments a system which is precisely tailored to their needs.

2.10.2 Decision support systems

Computers are also used to assist with more technically demanding maintenance tasks such as fault detection, fault diagnostics and decision support. These systems are neither CMMS nor MMIS in the conventional sense, but since they may be integrated with MMIS they should be considered here.

Vanneste and van Wassenhove (1995) describe a computerised tool that combines elements of several decision support models, to provide support to maintenance managers pursuing a continuous improvement programme. They observe that conventional MMIS are not able adequately to support managers since they are static in nature. Their approach is a closed loop cycle of eight activities, which is similar to

Deming's plan-do-check-act approach, also known as the Deming wheel. They recommend that this cycle should be embedded in a user-friendly and flexible MMIS. They regard hypermedia technology as very appropriate here, since it "... allows the user to navigate through the information system in a way that resembles the way of thinking in the mind...".

Lee (1995) presents a review of research into automatic fault detection and fault diagnosis techniques using methods such as neural computing and expert systems. He argues that these techniques should be used to enhance rather than replace human abilities, and explains how this might be done. He does not mention team-based maintenance. Further examples of the use of the computer to enhance human abilities in a proactive maintenance environment are described in chapter 3.

2.11 Maintenance Information Systems and Teamworking

In a comprehensive survey of the literature on team-based maintenance and CMMS, Boznos (1998) mentions several successful implementations of CMMS to support teamwork, but his survey of 71 manufacturing organisations produced results similar to Swanson's (1997). Boznos found 66% of companies using CMMS and using Swanson's list of modules he finds similar usage figures. In addition to the usage of various modules, Boznos asked respondents whether they had found these CMMS modules useful for either their RCM programmes, their TPM programmes or for facilitating teamwork. The results show that whereas respondents regarded their CMMS as useful in supporting RCM and to a lesser extent TPM, they did not generally feel that their systems were useful for facilitating teamwork.

Boznos also asked respondents to describe their usage of several typical additional features of CMMS, and also to state how useful these were in supporting RCM, TPM and teamwork. His results show clearly that respondents felt that the most useful specialised CMMS feature for facilitating teamwork would be e-mail support, but that only 17% of the systems used actually had such a feature. Another clear result was that all respondents felt that multimedia and hypertext features would be useful to support their RCM programmes, but not at all for facilitating teamwork. However, since only 8.5% of the systems used actually had these advanced features, it may be that respondents were unaware of the potential benefits.

As part of his research, Boznos visited five users of CMMS who stated that they used teamworking as part of their maintenance strategy, to evaluate the effectiveness of their systems for supporting teamwork. All the companies were in the automotive industry, except one - a soft drinks manufacturer. Interestingly, it was the soft drinks manufacturer who had been most successful in using a computer to support team-based maintenance. A summary of the results of these visits is given in Table 2-4.

Description of Company	Experience of CMMS and Teamwork
Soft drinks manufacturer	User-friendly windows based system developed in-house with involvement of users. System is believed to support TPM very effectively by providing feedback in exactly the form needed. Not used by operators and very little used by maintenance staff, since paper systems are felt to be effective enough.
Steering systems manufacturer	Successful TPM programme started in 1996 and supported by kaizen activities. CMMS is 10 years old and not user-friendly. Data entry carried out by designated clerk instead of operators or maintainers, however system has supported TPM through production of downtime reports. Aim to use a module of new ERP system to support maintenance in future.
Automotive wheel manufacturer	Company has tried to introduce TPM with limited success. Computerised data collection system used to collect downtime data but TPM seems not to have received required management support. Maintenance department has recently bought a CMMS for their own use without considering how it might support TPM. CMMS system expected to be integrated with future ERP system.
Luxury car manufacturer	Successful TPM user whose maintenance activity has been supported by computers since 1984. However, present system is not millennium compliant and will be replaced by recently specified CMMS. New system has been specified with full involvement of users and is intended to support teamwork in many ways including provision of CAD drawings, access to intranet and e-mail facilities. Intend to integrate CMMS with planned ERP system.
Car body pressings plant	Successful TPM user. Recently specified and installed new CMMS which has had some commissioning problems. Intended to support teams through use of touch screens for data entry, on-line provision of drawings and eventual integration with factory management systems and condition monitoring systems.

Table 2-4 Summary of company visits (source: Boznos, 1998)

2.12 Summary of Chapter

This chapter has described several different kinds of maintenance activity and outlined the development of maintenance as a technical discipline. Some recent developments in maintenance have been described and the emergence of maintenance as a competitive strategy has been noted. Since much of this thesis has been researched in the automotive industry, attention has been drawn to the importance of maintenance of complex automated equipment such as that found in automotive manufacturing. For the same reason TPM, which is common in automotive factories, has been described in detail.

A distinction has been drawn between the computerised systems intended for use by maintenance managers and those designed for maintenance technicians. CMMS and MRPII (or ERP) have been shown to be applicable to the former, whereas automated fault detection and diagnostic systems have been shown to be relevant to the latter.

A significant weakness of conventional approaches to CMMS is that they do not directly support teams of maintainers and operators on the shop floor. When IT is used in a TPM environment, computers are often used to collect breakdown data instead of providing the teams with information to facilitate their maintenance work.

The chapter concluded with the results of two surveys of the use of CMMS in industry. These surveys demonstrate how these software tools are used to support maintenance managers, how they often have little relevance to teamworking and are used rarely by production operators. The next chapter looks at human-centred information systems and considers how this approach may be applied to develop a CMMS that might be more generally suitable for TPM.

3. Human-Centred Information Systems for Manufacturing

3.1 Introduction

Chapter 2 has covered what might be called orthodox approaches to CMMS where the computer is used to assist the maintenance manager. However since many organisations have adopted a team-based approach where the process operator is much more involved in maintenance tasks, it may be argued that a different type of maintenance information system is more appropriate. This chapter therefore provides a brief review of some of the literature on information systems that are designed specifically with the user in mind - the 'human-centred' approach.

Most writers on information systems recommend that system designers should consider the user environment when designing the system, and there are several approaches to this. Lean manufacturing represents a significant change in the user environment, such as the use of teams and the role of worker knowledge in continuous improvement programmes. It follows that the human-centred approach to information systems may be required to support lean manufacturing.

This chapter looks at several approaches to the design of human-centred information systems including two applications of the socio-technical systems approach. There is also a brief description of the application of artificial intelligence techniques to maintenance, which explains the limitations of this approach in a lean factory. The growing field of computer-based training and the related subject of electronic performance support systems is described before looking at the more human-centred Scandinavian alternative of interactive technical support systems.

Finally the chapter covers the subject of hypermedia systems as a technology to support group work, knowledge management and empowerment of workers. This includes examples of the application of hypermedia technology to document management and logistics support.

3.2 The Systems Approach to Maintenance

Visser (1995) views the maintenance system (which need not involve computers) as a complex subsystem of the manufacturing enterprise. As such it has complex relationships with the other subsystems of the enterprise, which are better understood by adopting a systems approach. Citing several authors on maintenance, Visser argues for a framework for maintenance system analysis in order to speed the flow of materials and information involved in maintenance, and thus improve the profitability of an enterprise. He regards the current popularity of TPM as indicative of the need for better management of the maintenance function, and is critical of the conventional approach to CMMS, which he regards as a burden rather than an aid to maintenance.

Visser describes the systems approach as a means of dealing with complexity and 'systems thinking' as a framework of thought that allows one to deal with complex problems in a holistic manner. Hard systems methodology may be applied to well structured problems whereas soft systems methodology is more appropriate for poorly structured situations - typically those involving human behaviour. Both approaches have in common the desire to reduce the complexity associated with a problem and Visser lists a number of systems approaches including those of Checkland (soft systems) and Beer (organisational cybernetics).

3.2.1 Systems for teams

Caldwell (1994) compares the cybernetic and socio-technical approaches to systems design and argues for a combination of these very different approaches, to enable more rapid and effective communications in a team environment. This is necessary where team members experience tight deadlines and complex problem solving requirements. Although Caldwell does not mention maintenance, these are certainly features of most breakdowns. Caldwell argues that although it is useful, the cybernetic systems approach has two weaknesses in terms of its analysis of both team performance and the behaviour of human-machine systems in the context of their environment. The socio-technical systems (STS) approach, which would include cultural and social influences on a group of people, is strong in precisely these areas. For this reason Caldwell argues for a blend of these systems approaches.

3.3 Human Factors

In chapter 2 the human factor in maintenance was explained by reference to Kahen's (1997) model of a technology system. Kahen takes the cybernetic systems view when he states that "in a man-machine system, the human element is now considered as an 'information processor' and 'machine controller'". In his view, this means design processes should be more human-oriented than technology-oriented. He argues that a human-centred strategy should be at the heart of the four technologies of total quality control, just-in-time, total productive maintenance and flexible automation.

Benders *et al* (1995) outline some European human-centred approaches such as ESPRIT, FAST-MONITOR and UTOPIA and anthropocentric production systems which they regard as 'symbiotic' since they stress the necessity of co-operation between technical and social scientists when designing production systems.

3.3.1 Anthropocentric production systems

Wobbe (1995) describes the anthropocentric production systems (APS) approach in more detail and he argues the need for a fundamental change in European manufacturing culture (he uses the German word *Leitbild* which might be translated as *paradigm*) in order to compete with the Japanese. It is argued that APS are more suited to the demands of today's market, which are no longer met by the mass production Leitbild. Wobbe shows APS to have the following characteristics:

- Comprehensive use of human abilities and performance
- Permanent learning of the workforce and facilitating corporate structures
- Decentralised production units
- Cut-backs in the division of labour
- Collaborative forms of organisation

- Adapted technologies

He argues that communications between white-collar and blue-collar workers are central to competitiveness, and that barriers to such communications do not exist in Japan. In his view, these barriers are lower in Scandinavia and Germany than the rest of Europe. Wobbe makes a comparison between Germany, France and the UK in which German manufacturers are shown to have blurred the distinctions between technical and supervisory staff and between maintenance and production workers. For this reason, he feels that the chances for success of the new Leitbild may be greater in Germany and that the German industrial culture might explain the strength of German industry in the machine tool, automotive and electromechanical engineering sectors.

3.3.2 High performance work systems

In the US, a similar approach to APS called 'high performance work systems' is advocated by the Work and Technology Institute in a booklet entitled *Smart Workers, Smart Machines* (Jarboe and Yudken, 1996). The authors identify globalisation of markets and production methods as the factors that are forcing US firms to be more competitive. They argue that only a human-centred approach that harnesses the knowledge, intelligence, insights and experience of all employees can achieve the rapid flexible production of goods and services that will meet customer needs at affordable prices. They identify the European approaches to human-centred production mentioned above and the use by the Japanese of such high performance techniques as continuous improvement, worker involvement, teamworking, extensive skills training and an emphasis on quality. In a section covering technologies that enhance workforce skills, they identify computer-based multimedia systems, advanced expert systems, advanced simulation software and virtual reality technology, which they say can all be applied to advanced training environments.

3.3.3 Human factors in advanced manufacturing

In 1993 an international group of industrial managers, engineers, consultants and researchers met at the international conference on human-computer interaction (HCI International '93) to discuss the subject of human factors in advanced manufacturing (Karwowski *et al*, 1994). The two objectives of the meeting were to:

1. Discuss what could be done to improve the human factors related problems in advanced manufacturing (it was assumed that this would lead to increased profitability and customer satisfaction).
2. Develop an international agenda for R&D on human factors in advanced manufacturing.

Following a brainstorming session, 17 initial topics for discussion were agreed. These included human roles in advanced manufacturing technology, human factors in maintenance and skill-based automated manufacturing. Following much debate and discussion which included the need for adaptive information systems to connect autonomous work groups and the need to consider workers' 'tacit knowledge' of advanced manufacturing processes, a list of 43 topics for long term R&D were identified. Of these, 22 were concerned with developing new tools and techniques for providing information. Summarising the topics, the authors state that research should be carried out to help industry develop several capabilities including technologies that leverage the skills and knowledge of users. Examples of such technologies are condition monitoring, database management and computer-supported co-operative working.

During the discussions, a socio-technical approach to human, organisational and technology issues was promoted. The most significant contribution to this was felt to be the ACTION tool (Majchrzak and Finley, 1995). ACTION is a computer-based expert system for the socio-technical design of organisations, which has been widely tested on manufacturers and which is intended to address some of the perceived shortcomings of the STS approach.

3.3.4 Socio-technical Systems and Advanced Manufacturing

Many researchers argue that the socio-technical approach is essential to derive the benefits from advanced manufacturing technology (AMT). Dale (1995) argues that the reason that the US has not been as successful in implementing CIM as the Japanese or Europeans is a failure on the part of many US companies to take account of the effect of organisational culture. He argues that General Motors' expensive failures with AMT in the 1980s were due to their attempt to introduce the technology first and then try to change their social systems to fit. Those companies who are successful with CIM tend to be those with a heavy orientation towards people.

Blumberg and Gerwin (1984) made a similar point more than a decade earlier where they argued that too much attention had been paid to technical innovation and not enough to the adjustments needed in organisations to accommodate the new technology. They also took a socio-technical approach to the analysis of the problems with early CIM systems. Among the most serious problems with CIM is the maintenance of electrical and electronic systems. They quote one UK company that spent two hours on electrical and electronic maintenance per eight hour shift. Their study found that new technologies are often not fully understood in terms of their likely failure modes, even by the vendors. The authors also point out the difficulties of training and retention of maintenance workers with the skills required to troubleshoot the very complex systems being installed.

Their recommendations are that companies adopt less complex technologies and adapt their existing socio-technical systems to the needs of CIM. Examples of the latter are the development of smaller scale computing capabilities to break the dependence on the corporate mainframe, and alternative equipment designs that stress the interaction between humans and the machine. They also recommend more in-house training programmes, more time for direct and indirect workers to become familiar with the operation and maintenance of CIM technologies, and the adoption of less hierarchical organisational structures such as semi-autonomous work groups.

3.4 Human-Computer Interaction

As with manufacturing systems, there are also arguments for a human-centred approach to the development of information systems. Eason (1991) makes the point that systems do not govern behaviour as much as users behaviour governs system usage, and hence influences uptake. Humans are the dominant partners in human-computer interaction since they will only use a system if it proves useful to the task. Uptake will only occur if information system designers adapt their designs to the user and not vice-versa. Eason shows how human-computer interaction occurs at three levels (Figure 3-1).

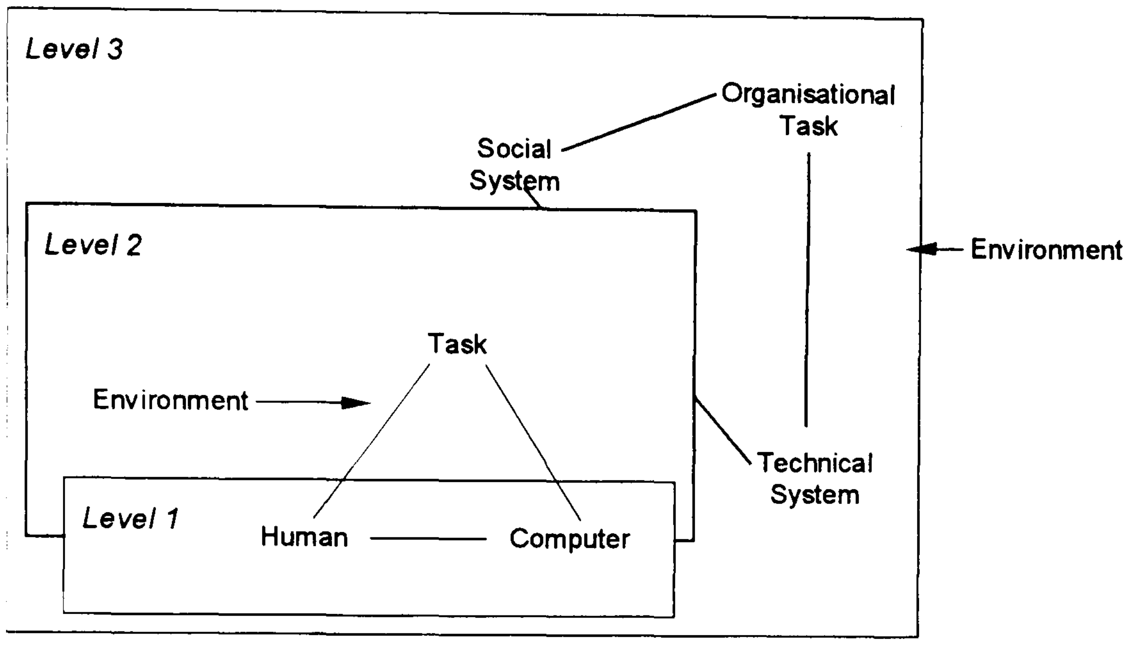


Figure 3-1 Three levels of analysis for human-computer interaction (source: Eason, 1991)

3.4.1 Individuals and their computers

Many HCI researchers work at level 1 where there have been great advances in the interface between the individual user and the computer. The graphical user-interface (GUI) is one example of the effort on the part of the computer industry to develop more user-friendly systems that need less specialised training. Other examples are the development of speech processing, which is particularly useful for those who dislike typing, and the development of wearable monitors in the form of headsets and spectacles. Both developments are of interest in the field of maintenance where users' hands may be occupied and where a desktop monitor may not be convenient (Wilson, 1996). Eason (1991) describes the use of touch screens as part of a level 1 interaction and these too may be of use in a maintenance information system.

3.4.2 External tasks

At level 2, as well as what Eason (1991) calls 'internal tasks' one must consider the human-computer relationship in terms of the reasons why the user has chosen to interact with the computer, the 'external tasks'. At this level, predicting user behaviour is more difficult since there are so many more factors to consider such as the knowledge of the user, the clarity of the task purpose, user motivation, organisational context etc. One way of evaluating the success of a prototype design is through usability studies where usability is defined as 'the effectiveness, efficiency and satisfaction with which users can achieve specified goals in a particular environment' (Eason, 1991). Eason describes early systems that were only appropriate for highly structured tasks because of the inflexible way in which they constrained the user interaction. When systems of this type were used to support unstructured tasks such as problem solving, users rejected them. As a result, systems to support such activities are now designed to 'shift the locus of control to the user'. This is of particular relevance to a maintenance information system.

Eason mentions the development of expert and knowledge-based systems of which the most common practical examples are those designed to support medical diagnoses. However he refers to the main drawback of such applications, which is the question of incorrect diagnosis. If a patient dies as a result, does the responsibility for the death lie with the software engineer who designed the system, the 'expert' whose knowledge has been elicited or the computer? A similar but less dramatic problem exists when expert systems are used for fault diagnosis of machinery.

3.4.3 Organisational context

An example of research into HCI at level 3 is that which is concerned with computer support of co-operative work (CSCW). At this level, researchers consider the social context in which organisations use technologies such as electronic mail, electronic conferencing and video conferencing. A weakness of CSCW research is a tendency to be concerned with group communications between peers, particularly in academic and research environments. In this sense it is less relevant to the social context of the factory (Eason, 1991).

The effect of human and organisational factors upon the performance of IT is explored by Clegg *et al* (1997) in a study in which they interviewed 45 of the leading experts in the organisational aspects of IT. Among their findings was that 80-90% of IT investments do not meet their performance objectives, the main reason being inadequate attention to the human and organisational aspects of IT. More specifically they identified poor management generally, poor project management, poor articulation of user requirements, inadequate attention to business needs and goals and a failure to involve users appropriately. Some of their interviewees held the view that some supposedly business-led organisations are in fact led by their IT people who have to justify their existence. More generally a technology-centred attitude, which is vulnerable to vendor hype, was given as the reason for many failures. Eason (1991) regards user participation in the design process as one solution to such problems.

3.5 Artificial Intelligence and Knowledge-based Systems

The issue of responsibility for incorrect diagnosis was mentioned above. Clancey (1993) makes a similar point in relation to knowledge-based systems (KBS). In his view, knowledge about a fault condition depends upon knowledge of the history of the fault. This is illustrated with a story of a Stanford computer that crashed every October when the first heavy rains fell. The fault was eventually traced to rain on the phone lines to Santa Cruz that caused spurious control-C characters to swamp the computer. This is the kind of fault that could neither be predicted nor solved by swapping circuit boards. If an expert system were used to support system maintenance, it would need to be updated as new knowledge of such failures was generated. Clancey argues for a shift in perspective for KBS research in which tools would be provided for users to reflect on their practices in discussions with each other. He calls for knowledge engineers to collaborate with social scientists in designing software tools to enhance worker capabilities.

Jahoda (1989) contrasts the optimism that surrounded the birth of artificial intelligence (AI) with the mixed mood of some of today's writers who speak of an 'AI winter' and one of the early pioneers who sees all the major AI problems as intractable. She describes a basic inferiority of AI compared to humans in that computer systems cannot transcend their highly specific input, see analogies with other issues, deal with unforeseen contingencies or freely associate.

Commenting on the commercial failure of knowledge-bases systems, Mitev (1994) argues that this is due to knowledge engineers having taken a technology-led approach which has only recently (and necessarily in her view) changed to a business-led one. She outlines a structured methodology for designing business oriented systems which will take account of human and organisational issues among other factors, but she does not refer to any of the fundamental drawbacks of this technology from a human-centred systems point of view.

The AI community has often tried to codify maintenance activity (Turban and Aronson, 1998), and capture workers' experience to make it available to other team members (Fischer *et al*, 1996). However it may not always be the case that workers (blue or white collar) would give up their knowledge and experience easily, and they may disagree over what constitutes good practice.

3.5.1 Expert systems, multimedia and hypermedia

Fuerst *et al* (1994/95) describe three examples of expert systems which are integrated with multimedia information. In each case, the application makes use of multimedia to provide rich knowledge sources or to facilitate the knowledge acquisition process. They point out that while the user-interface for an expert system tends to be in the form of a question and answer dialogue, in the case of complex tasks this communication can be greatly enhanced by multimedia objects. Examples of such objects are video, pictures, photographs or animation and in the future, voice recognition. As an example of such a complex task, they mention the operation and maintenance of a complex letter-sorting machine that uses an expert system supported by a multimedia interface. At present such integration is not readily supported, and in their view is most likely to proceed by adding multimedia functions to an expert system shell, rather than vice versa. None of the systems they describe appear to be easily updated by users, instead expert intervention is needed.

Angeli and Chatzinikolaou (1995) describe an expert system called HydroPro that is used to diagnose faults in a hydraulic system. HydroPro features a graphical user-interface and hypermedia (see paragraph 3.11). In this system, the diagrams of the hydraulic circuits are used as a navigational aid to help users to trace the causes of a fault along the same paths as the oil flow. Another benefit of this approach to the structure of the information is that the knowledge base can easily be extended to add other topics or to be applied to other similar hydraulic systems. Although the expert system uses a rule based approach to problem solving (which means the rules have to be programmed by the expert), the graphical user-interface makes use of the hydraulic circuit diagrams to illustrate the question and answer dialogue with the user. It is not clear whether there is any attempt to enrich the diagrams themselves with hyperlinks to other diagrams. The users of HydroPro are assumed to be engineers and there is no discussion in the paper of the social context in which this expert system will be used. The authors describe future enhancements to the expert system, which include connecting it via a data acquisition system and suitable sensors to the hydraulic system itself. This would allow the expert system to be used for condition-based preventative maintenance.

Torvinen and Milne (1996) describe a diagnostic expert system for maintenance of Flexible Manufacturing Systems (FMS). The system features automatic data collection via sensors that monitor the condition if the manufacturing system and the error codes generated by a fault are used to open a hypermedia maintenance manual at the correct page. In this case, the authors do recognise the need to allow users to input new faults not known to the expert system or to improve existing procedures. They explain how this might be achieved through a scratchpad that could be used by the system manager to update the database. It is not clear whether this approach was actually used in practice, and in discussions between the researcher and one of the authors it was found that none of the pilot sites practised any form of TPM.

3.5.2 Enhancement of an expert diagnostic system through hypermedia

An expert diagnostic system for autoclaves and bonding presses was developed from a conventional expert system to a hypermedia system (Bates, 1991). The aim of the system was to assist autoclave operator to respond rapidly to autoclave cure cycle anomalies during the manufacture of expensive composite components. A large amount of process knowledge had been documented by autoclave operators based on their accumulated experience of control of autoclaves. This knowledge was then presented in prototypes of two decision support systems. The first system was developed using a commercially available diagnostics package that used a traditional rule based approach to problem solving. This was a text-based system whose ability to present graphical information was poor. The system questioned users whose answers were then processed by a backward chaining inference engine to lead to a solution.

This system proved both expensive to produce and unpopular with users so an alternative hypermedia system was developed using the same knowledge base. The second prototype was a true hypermedia system featuring a mouse driven graphical user-interface and making extensive use of graphics, photographs and sounds. The paper concludes that the hypermedia system was both more popular and cheaper to implement than the traditional KBS. One drawback of the hypermedia system was the lack of a dedicated knowledge acquisition module, but this was more than compensated for by the ease of use and the ease with which the system could be updated - by users in some cases. Although team-based maintenance is not mentioned, the hypermedia system represents a means of capturing and sharing process knowledge.

3.5.3 Human-centred expert system for designers

Kirby (1995) describes an artificial intelligence approach to control systems design called Computer-Aided Control System Design (CACSD). An interesting example of such a system is a hypertext tool called Numerical Methods Advisory System (NUMAS) which is a decision support tool for designers of control systems. Kirby describes NUMAS as an example of an alternative technical solution to traditional KBS, which places the user in control of the problem solving process. KBS techniques were used to structure the information in the NUMAS tool, but the result was a hypertext method of knowledge representation as opposed to the more traditional automated rule-based approach. Kirby concludes by suggesting that systems such as NUMAS might point the way to an alternative role for AI/KBS technology to develop ways of storing information which might empower problem solvers rather than seek to automate the problem solving process.

3.5.4 Development of process knowledge

The importance of facilitating the increase in knowledge of industrial processes is emphasised by Bohn (1994) who describes eight stages of knowledge about a process from complete ignorance to complete knowledge. He makes the point that for advanced manufacturing technology, since many variables are at stage four or below, the level of knowledge of the processes must be raised quickly. However, customer pressure leads to frequent introductions of newer processes so that an organisation may never get to stage eight knowledge, and must therefore combine rapid learning with the ability to operate with 'immature' technologies. This has implications for maintenance information systems designed to support advanced manufacturing technology. Such systems must facilitate rapid learning about the processes they support and be easy to update as knowledge grows.

3.6 Organisational Learning

A growing field of academic enquiry in which information systems are used to enable continuous improvement is that of organisational learning. Insights from this field have been used to assist workers improve maintenance and set-up processes. In his book *The Reflective Practitioner*, Schön (1983) describes an action-breakdown-reflection cycle that is followed by professionals. In this cycle, practitioners engage in a situated action until their expectations are not met and they experience a breakdown in the current work situation. At that moment, they stop and reflect on how to overcome the breakdown before proceeding. These breakdowns in situated action present opportunities for learning because there is an opportunity to construct new contextualised knowledge while solving a personally relevant problem (Sumner and Stolze, 1996). This theory could be applied to the operation and maintenance of a manufacturing process. Much of the knowledge about the operation and possible failure of the process is held in the heads of the process operators and this fact underlies much of TPM. Any maintenance information system that is intended to operate in a TPM environment should allow operators to update the system's knowledge base thereby enabling the benefits of the workers' knowledge to be shared. It is interesting that Schön refers to contextualised knowledge. By using hypermedia to link chunks of information which represent process knowledge, the context can be preserved (see later).

When discussing the critical role of learning in the new knowledge economies, Zuboff (1988) described 'smart machines' that could assist in actively 'informating' practitioners as they work. In the case of a maintenance information system, this could be achieved by including training material, engineering drawings, parts lists and descriptions of procedures. The resulting system would then have a role in training the workforce as well as forming an archive of relevant documents.

3.6.1 Machine setters as reflective practitioners

Passarge and Binder (1996) describe the use of a hypermedia system to support the training of machine setters in the spring manufacturing industry. The system described was designed in collaboration with expert machine setters and featured video clips of their agreed best practice. The system was intended to improve the training process for new setters by supporting the existing training techniques. Using Schön's (1983) terminology, the study treated the machine setters as reflective practitioners. The study found that the hypermedia system was well received by the setters who felt it could be used both to train new setters and to stimulate discussion about the process with outsiders such as grinders, inspectors and supervisors. The study concluded that hypermedia training tools can have a role to play in building and sustaining reflection and dialogue.

3.6.2 Corporate memory

Bernardi *et al* (1998) describe an information system designed to realise a 'corporate memory' and which is used in the maintenance of complex coal mining equipment. Before describing the information system, they make the distinction, which is common in the study of knowledge management, between tacit and explicit knowledge. This distinction refers to the difference between personal subjective knowledge such as know-how, insight and intuition that is called 'tacit knowledge' and more formal 'explicit knowledge'. The latter is relatively easy to document and transmit between individuals, but the former is more difficult and often requires training and practice to develop. They then describe the difference between top-down learning such as a management instigated training course, and bottom-up learning in which operators who have gained useful insights during their work may transmit this process knowledge to the rest of the organisation. In the context of maintenance, knowledge of complex processes (which may often be tacit) is very useful to the organisation, and it is therefore the purpose of their maintenance information system to make such knowledge explicit, in order that it can become part of the organisational memory. The conversion of tacit knowledge to explicit knowledge is known as 'externalisation' and the opposite process is known as 'internalisation' (see Figure 3-2).

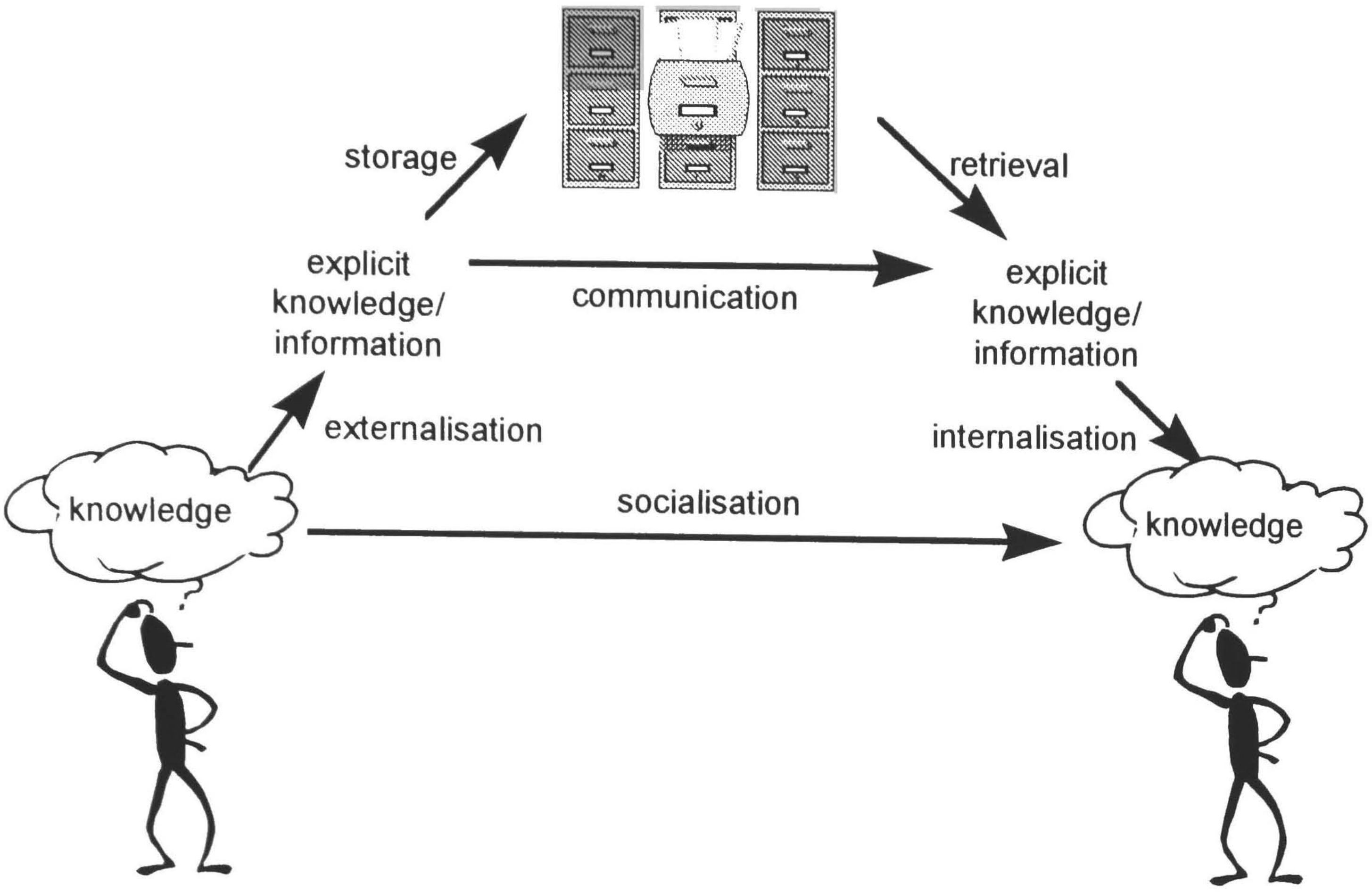


Figure 3-2 Knowledge conversion and learning process (source: Bernardi *et al*, 1998)

Bernardi *et al* describe three different approaches to the conversion of tacit to explicit knowledge:

1. The conventional approach in which people make tacit knowledge explicit by writing it down on paper.
2. The expert system approach in which knowledge is captured in the form of rules. This approach can hinder the exchange and evolution of knowledge.
3. A hybrid approach in which knowledge is first written down conventionally before being entered into a computer for electronic storage.

The expert system described by Bernardi *et al* is called an ESB (Elektronisches Storungsbuch) and it takes the form of a set of log entries called 'event sequences' which each describe the occurrence of a fault, its diagnosis and eventual solution. These are created by users as they maintain the mining equipment, and are validated by an expert before being prioritised and added to the knowledge base. The validation process may involve editing of the information in the event sequences and their prioritisation is to distinguish between information that is important for future fault diagnosis and that which is for archive purposes only. As with the HydroPro system (Angeli and Chatzinikolaou, 1995) the structure of the knowledge base reflects the structure of the component hierarchy of the machine/system itself. The system communicates between the control station on the surface and the mining equipment (at the coal face) via a telephone line and in the first three months of use it proved popular and successful. A more formal evaluation of the effectiveness of the ESB is expected in the future.

3.6.3 Documentation of the experience of maintenance

When a new manufacturing process is introduced the designers provide explicit knowledge in the form of documentation, usually a set of manuals and drawings. Fischer *et al* (1996) describe a system called DIADOSYS that allows maintenance and production workers to add to this knowledge by documenting their own experiences for the benefit of their co-workers. Maintenance is seen as an example of experience-based behaviour that is usually difficult in a complex automated environment due to the following factors:

- Opaqueness of technical phenomena and processes
- Rapid rate of innovation in machinery and software
- Convergence of originally separate metal, electrical and information-related processes
- The networking of formerly separate areas of production

Using DIADOSYS, maintenance workers can document their experience of fault finding in the form of chains that represent cause and effect relationships. Having been documented in this way, the chains lead a user from the observed phenomenon to the root cause of a fault. The chains are shown graphically on a computer screen and it is possible to link other information to the chain such as references to the user handbook, references to specific tools etc. New chains are stored in the system until they can be checked and validated by a supervisory group (a team of skilled workers) whose authority allows validated cause and effect chains to be made available to all workers as a set of standardised procedures. It is intended to use DIADOSYS as a training tool as well as a dynamic knowledge base (Fischer *et al*, 1996). It is not clear whether DIADOSYS stores information according to any recognised standards or how it can access vendor documentation that exists in a range of different data formats.

Murray *et al* (1994) describe an innovative system called 'Plant Manager' which was designed for BP Exploration in the Forties Field. BP is adopting new approaches to the management of offshore operations, including TPM. Plant Manager fits within this programme since it is intended to empower offshore workers with operational expertise that was traditionally resident onshore. There is no attempt to use Plant Manager for activities such as scheduling and inventory control, instead the aim of the system designers was to provide offshore personnel with links and tools to collate and manage the information they needed to do their jobs. This was achieved through a user-centred system design process. Central to this system is the display of operating procedures and CAD drawings of the plant called process and instrumentation drawings. The use of CAD means that the drawings contain additional data on component parts that is embedded in the drawing itself and made available to users. The links between drawings are achieved without altering the format of the CAD data by using labels on the drawings themselves as the link anchors. Plant Manager allows users to update and amend information where appropriate, and also to mark up the drawings. A supervisor validates any changes before they are incorporated into the system. In this way, the system allows workers to document and share their experiences, which is appropriate for the dynamic environment in which they work (Murray *et al*, 1994).

Although Plant Manager can exchange data with most major CAD systems, it is not clear whether this is achieved by providing a viewer for each different CAD format or by using a neutral file format such as IGES. Plant Manager is an example of a closed hypermedia system compared to an open system such as Microcosm (see later).

3.7 Computer-Based Training

Another way in which computers are used to improve the performance of maintenance workers is through computer-based training (CBT). Lindsey and Flowers (1995) describe a common problem for maintenance workers, which is the vast amount of information needed to support the range of different assets in the average factory. They quote an example of an automotive manufacturer with 300 machine tools from 48 different vendors. The complexity represented by this variety of assets forces the maintenance workers to seek assistance from engineers and third-party experts in too many cases. The use of CBT in the classroom and on the shop floor is proposed.

Several options for training are compared including off-site classroom based training, interactive video (e.g. videodisk) and CBT. The ability to interact with the trainer is the main advantage of classroom based learning over videotape, but the drawback of off-site training is the cost. This cost can be reduced if the training is provided on-site, but the cost is still high. CBT offers the potential for dramatically reduced cost as long as the economies of scale are available through re-use of most or all of the material. Although CBT does not imply multimedia, most modern CBT packages take this approach to creating a highly flexible and creative learning experience. Lindsey and Flowers call their computerised tool an electronic performance support system (EPSS).

Another example of a CBT system for manufacturing is given by Kasvi *et al* (1993). CATS !! (sic) is a multimedia system that combines text, digitised speech, still images and video. It was authored using *Multimedia Toolbook* from Asymetrix. Following a description of the system, it is concluded that modern manufacturing now demands more than conventional CBT. Interactive information support is proposed, in which information is available both during initial training and subsequently during operations. The aim is to supplement the memory of workers by providing the right support information, at the right time, in the right place. Subsequent publications from the same authors develop this theme and discuss it in more detail (see paragraph 3.9).

3.8 Electronic Performance Support Systems

EPSS are a relatively new type of system that are intended to "deliver the right knowledge at the right time" (Cole *et al*, 1997).

The main characteristics of an EPSS are the (relative) absence of any need for training, the integration of the software in the user's performance and the understanding that *performing*, not *knowing* is the key to success in a modern business environment. An example is a troubleshooting system used by a software help desk operator. It would be impossible for every help desk operator to know the answer to every problem described by every caller, but the EPSS can assist the operator to guide the caller to the solution. Notice that for both the operator and caller, learning may or not take place, but a good EPSS allows the required performance to be delivered (Cole *et al*, 1997).

3.8.1 EPSS for maintenance

Much of the EPSS literature discusses support for users of software such as a word processor (Gery, 1995) or activities outside the factory such as a system to ensure that a sales team always has the latest product information (Cole *et al*, 1997). However, the EPSS described by Lindsey and Flowers (1995) is used to augment the memory of maintenance workers. In their opinion, the success of any EPSS can be measured by the ease with which the information database (or 'infobase') can be created, accessed and updated. The infobase is a collection of all applicable information regardless of source, examples being maintenance histories and procedures, engineering drawings and specifications, parts lists, safety procedures and training documents. Three types of information are described; usable information, unusable information that is easily convertible, and raw information. Usable information is usually in digital format already, examples being word-processed documents or CAD drawings, even though these may need conversion. Easily convertible information is usually not available in digital form and must be captured by scanning and digitisation. An example is a typed document that might be scanned and processed through optical character recognition (OCR) or an engineering drawing that was produced by hand. Raw information can be very difficult to capture, but also very useful. Examples might be tacit knowledge in the heads of the workforce, notes annotated to drawings, sketches pinned up on a controller cabinet and personal notebooks.

Lindsey and Flowers (1995) also distinguish between structured and 'free form' infobases. The former is a more rigid design that is created by compiling information from a variety of sources into a fixed application. Any changes require recompilation, destruction of copies of the old infobase and distribution of the new one. A free form infobase, on the other hand, is the result of linking particular pieces of information (without compilation) from a variety of sources and presenting them to the user as a support system without compilation. This would typically be achieved over a network such as a company Intranet. It is argued that it is much easier to ensure that the information presented to users is current when using a free form infobase. As long as information at the domain level is maintained, then the infobase as seen by the user is automatically maintained through the links. The structure of a free form infobase is shown in Figure 3-3.

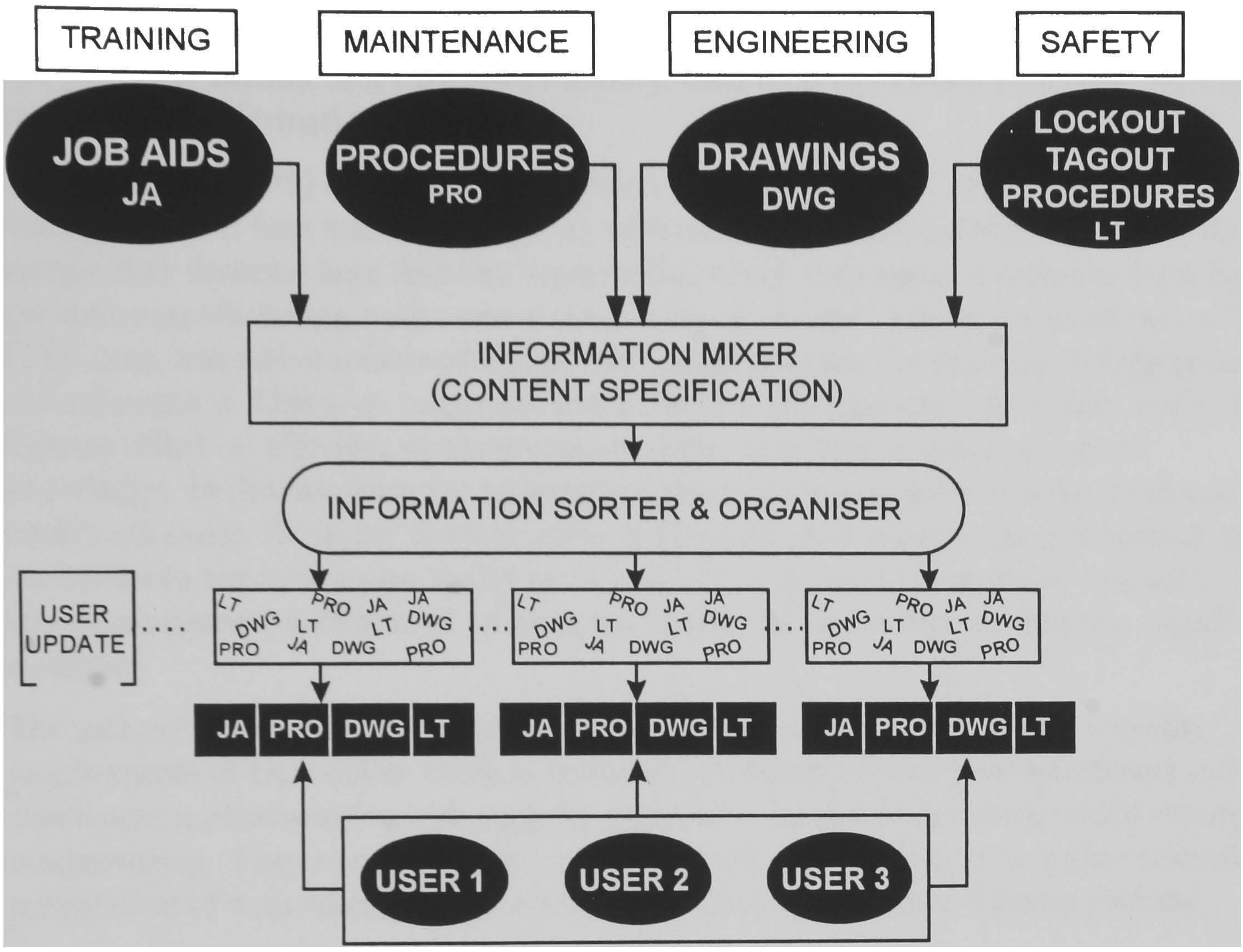


Figure 3-3 Structure of a free form infobase
(source: Linsdey and Flowers, 1995)

3.9 Interactive Task Support Systems

A related concept to EPSS is that of interactive task support systems (ITTS). This is a concept that originated in the Laboratory of Work Psychology and Leadership of the Helsinki University of Technology in Finland. The ITTS concept as described by Kasvi *et al* (1996), appears to be a response to the emphasis in EPSS on the reduction of both training effort and human interaction. The proponents of ITTS are keen to stress the quality of working life and they intend that ITTS should enhance networks of social interaction rather than diminish them as an EPSS might. According to Kasvi *et al*, there are broadly four sources of information for workplace support:

1. Personal memory, where knowledge is often tacit and is gained through training, experience and reflective thinking.
2. The social environment, which includes co-workers and supervisors.
3. The physical environment, which can inform the workplace through good ergonomic design of tools and workstations, as well as visual aids.
4. The information environment, which includes hand-written notes, notebooks, work instructions and quality standards as well as computer-based support systems.

An ITTS should reflect the fact that when looking for supporting information, workers will generally consult first their own memory, then their workplace then their colleagues and lastly the information environment.

Eloranta *et al* (1995) describe an application of ITSS principles to production management for lean manufacturing. As with other ITSS developed by this team, the system they describe here features hypermedia, which they argue is essential for a highly dynamic manufacturing environment since it can save time looking for information. The ITSS is an interactive multimedia tool that is used to assist the decision making process, not automate it. This is an important distinction for a human-centred system and it also focuses effort on effective decision making rather than careful maintenance of knowledge. In this situation the information need not be complete or even consistent in a traditional sense. To assist decision making Eloranta *et al* suggest using simulation and animation to see how a plan might work in practice, as well as computer-mediated voice communications which are felt to be easier to use and faster than written (i.e. typed) messages.

The authors discuss several areas for further work such as addressing the usability requirements of blue-collar workers (who are intolerant of poor user-interfaces) and the construction of interactive task support systems by users without the need for computer programming. They also write that an ITSS should not take longer to author than the preparation of equivalent printed work instructions or traditional training material.

3.10 Multimedia

Gunasekaran *et al* (1996) describe multimedia as "the melding of text, sound, photos, and even video to create dazzling documents and presentations". In its broadest sense, the term 'multimedia' could be applied to any form of communication in which information is carried simultaneously over more than one medium. Nowadays the term is usually applied to certain types of computer-based communication, and it is this type of application that is discussed by Gunasekaran *et al*. They define a multimedia system as "one that allows end users to share, communicate and process a variety of forms of information in an integrated manner".

3.10.1 Multimedia in manufacturing

Gunasekaran *et al* (1996) describe several applications of multimedia in manufacturing environments where the benefits are derived by using multimedia applications to improve enterprise integration. They list several manufacturing applications of multimedia (Table 3-1) including TPM where the main benefit is the ease with which such systems can retrieve, update and present large volumes of data to users whilst allowing a high level of interaction.

Some CMMS now include multimedia features. As well as presenting work orders, an enhanced multimedia CMMS can present accompanying instructions with illustrations and photographs, a detailed drawing, a copy of any relevant safety information such as hazardous material data sheets and similar information. It is claimed that this can result in faster and safer repair of equipment (Basta, 1994) but the main flaw in his argument is the low level of CMMS usage by maintenance technicians and production operators (Swanson, 1977). Perhaps a multimedia CMMS would be more acceptable.

Functional areas in manufacturing	Application areas for multimedia
Marketing	Sales promotion, advertising, customer service and feedback
Design and Engineering	Quality Function Deployment (QFD), CAD, CAPP, CAE
Production	FMS, CIM, Production Planning and Control (PPC)
Maintenance	Total Preventive Maintenance (TPM)
Accounting and Finance	Automated storage and retrieval system, ABC
Personnel	Training, demonstrations
Distribution	Automated warehousing operation, communicating with customers at different levels

Table 3-1 Multimedia applications in manufacturing
(source: Gunasekaran *et al*, 1996)

3.10.2 Animation and Graphics

The advantages of computer graphics over paper drawings have been explored by Bengtsson *et al* (1997) who looked at the methods used to plan factories and working environments. They considered four different types of workplace visualisation of which two were paper based and two used computer animation. Questionnaires were used to investigate the views of participants about the benefits of each approach for a range of manufacturing planning activities. One of the conclusions of the work was that for visualisation of the workplace (as opposed to the entire factory), computer animation was preferable to paper drawings for both static and dynamic planning issues. Those planning activities for which participants showed a clear preference for computer animation included workplace layout, manufacturing activities, repetitive work and machine functioning.

Rohrer (1997) discusses the use of computer graphics in manufacturing simulation and asserts that visualisation is the foundation of human understanding. Several reasons are given to explain why computer graphics are not more widely used including the perception that they are expensive to produce, trivial (because of their association with computer games) and bring only intangible benefits. However it is argued that since the mind has the ability to process large amounts of visual information quickly, animation should be used more and in some cases can actually provide better decision support than observation of the real system. This is because the animation can be made to show only that which is of interest without obstructions such as the factory roof, steelwork etc.

Many CAD systems now allow the generation of 3D solid models of designs that can be rendered to produce 'photorealistic' images. These images can be used in sales literature, presentations as well as to enhance the design process itself. CAD vendor Autodesk has a subsidiary called Kinetix who produce and sell the visualisation software 3D Studio

Max. Although most applications of this tool are in the entertainment and advertising industries, it is also used to solve engineering problems. Burrows (1998) describes an example of a car manufacturer who used 3D Studio Max to produce a simple animated sequence which was used to educate mechanics in their dealer network about a solution to a new engine problem. This was felt to be much quicker than waiting for an update to the service manual, which would have been more difficult to understand anyway.

3.11 Hypermedia

The difference between multimedia and hypermedia information systems is the way in which the user navigates between different pieces of information. Hypermedia systems allows the user to decide which path to take when presented with a number of options, and to control how long a piece of information is displayed before moving on (or back) again (Nielsen, 1990). The word *hypertext* is sometimes used to distinguish the linkage of information expressed only as text from more generic forms such as graphics or video. However the words *hypertext* and *hypermedia* are used interchangeably by Nielsen, since he feels that there is no need for a word to describe text-only systems. The author of a hypertext system has to include links between parts of each piece of information in the system. The reader then decides which path to follow through this information at the time of reading. This means that the structure of the information becomes non-linear compared to a conventional book that is read (usually) in a linear fashion. It also means that the author has less control over the way in which the information is communicated to the reader. Common examples of both hypertext and hypermedia are Windows help, the world-wide web, and CD-ROM based encyclopaedias such as Microsoft Encarta as well as bespoke systems authored using hypermedia authoring tools such as *Multimedia Toolbook* from Asymetrix. A simple hypertext with four nodes and nine *hyperlinks* is shown in Figure 3-4.

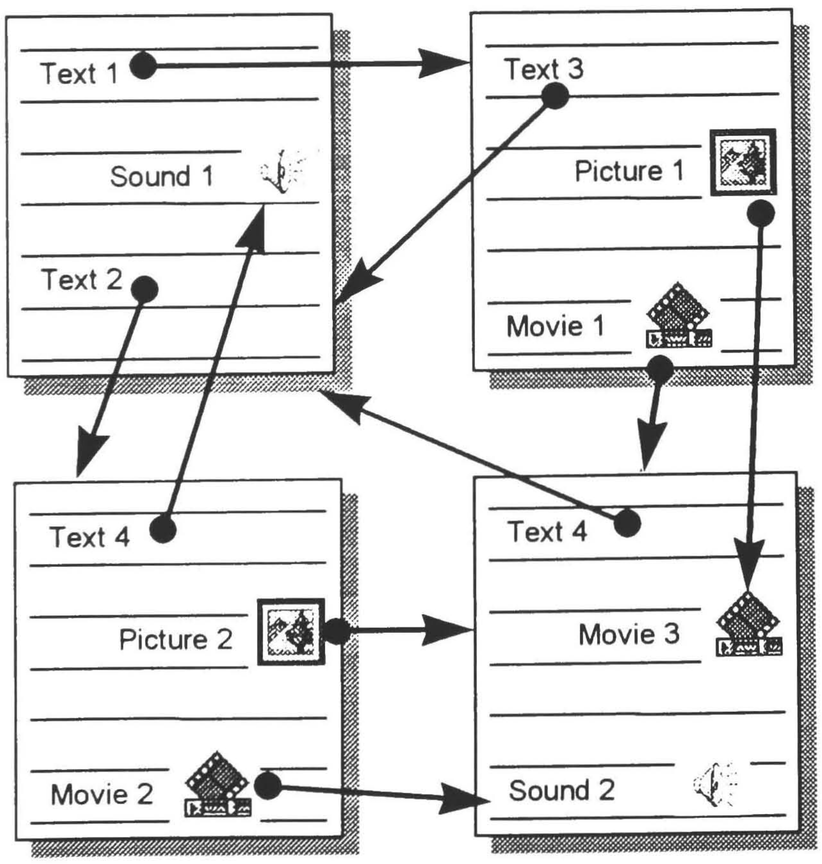


Figure 3-4 Structure of a simple hypertext with four nodes and nine hyperlinks

3.11.1 Memex - a conceptual hypermedia device

Hypertext is fundamentally a computer phenomenon and yet the inspiration for most hypertext research is a paper written in 1945 by the Director of the Office of Scientific Research and Development in the USA, Dr Vannevar Bush. Bush's proposed machine was called memex (a contraction of 'memory extender') and although it was never built it featured several technologies that were available at that time such as microfilm, photocells, dry photography, the cathode ray tube, voice synthesis and punched cards (Bush, 1945). Bush actually described some of his ideas for the memex in 1932 and 1933 and wrote a draft paper in 1939 but it was not until 1945 that his ideas were published in the *Atlantic Monthly* under the title *As We May Think* (Nielsen, 1990).

What was remarkable about the memex and what makes it a hypermedia device is the use of associative links between pieces of information. Bush saw the memex as a device to mimic the human mind, which operates by the association of thoughts through "an intricate web of trails carried by the cells of the brain". The memex would improve on the mind in the sense that its information would be stored with more permanence and the trails in the memex would not fade. Memex users would be able to link their trails with each other if they felt they were pertinent (Bush, 1945). Bush described a typical memex owner using the device to research the superiority of the short Turkish bow to the English longbow as used during the Crusades and then sharing his research with a colleague several years later. Reading the article at the end of the 1990s - it is available on the world-wide web - one is struck both by the number of Bush's ideas that have been implemented, and by how much there is still to do.

3.11.2 Open hypermedia systems

Vanzyl *et al* (1994) discuss the concept of 'open hypermedia' and they compare three hypermedia systems, Microcosm (see later), HyperTED (a Macintosh based system) and the world-wide web, from the point of view of their openness. In their view, an open hypermedia system would have to fulfil the following five criteria:

1. Size extensibility, which allows the number of nodes and links in a system to be extended by the user
2. Multiple and extensible media and link support. This distinguishes hypermedia from hypertext and in its strictest sense should allow a user to link to any digital media in any known file format.
3. Addressing abstraction. This would allow an open hypermedia system to retrieve information independently of network protocols. The hypermedia system must also allow other systems (such as a CAD system) to access the same information.
4. A robust linking mechanism that is invulnerable to changes in document content or location. This is in order to avoid the problem of 'dangling links'. There will always be a problem linking to a document that has been radically altered or deleted.
5. Document sanctity, which requires that the hypermedia system does not alter or mark up the source documents.

It is clear from the paper that the three approaches described are very different and that none completely fulfils the criteria for an open hypermedia system. Whilst the WWW is undoubtedly the most successful approach as shown by its phenomenal growth in recent years, it is not considered an open hypermedia system for two reasons. Firstly, its use of hypertext markup language (HTML) to define documents by embedding tags in the text which is then viewed through one of a number of browsers, means that the authors cannot completely control the presentation of information. HTML thus fails the document sanctity requirement. Secondly, there is no provision for link integrity at the file level so that if a file is moved or renamed, any attempt by a browser to link to information in that file will fail. This leads to the annoying 'dangling link' problem that is familiar to users of the world-wide web.

Hypermedia systems such as commercially available multimedia encyclopaedias are closed systems in that they cannot be updated and maintained by users. One has to buy the latest copy as the current one becomes out of date. A document such as a hypermedia quality manual, however must be constantly maintained, and for this reason is best authored using an open systems approach such as HTML or an open hypermedia tool such as Microcosm (Crowder *et al*, 1996). An open hypermedia tool can create hyperlinks between documents in common native formats such as rich text format (RTF) and bitmap (BMP). The approach taken by Microcosm is particularly innovative since the information describing the sets of hyperlinks (called 'linkbases') is separate from the source documents. This means that the source documents are not altered by the authoring process and can be maintained separately, and also that different linkbases can be defined for different purposes.

3.12 Hypermedia in Industry

There have been several documented cases of the use of hypermedia in industry. For the purposes of this thesis, *industry* has been taken to mean manufacturing and process industries as opposed to the service sector. It is helpful to distinguish between 'white collar' operating environments such as the design office and 'blue collar' environments such as the shop floor or the maintenance workshop. The uses to which hypermedia is put in industry depend upon the environment but most of the cases described in the literature are shop floor based.

3.12.1 Industrial strength hypermedia

Malcolm *et al* (1991) provide one of the most helpful descriptions of the claimed benefits of hypermedia information systems in industry. They describe how the integrative features of hypermedia could be used to support a large engineering enterprise such as an aircraft manufacturer. Examples are given of existing hypermedia applications such as training material, operations manuals and maintenance manuals. These are described as closed systems in that the hyperlinks were defined by the authors and fixed in the documents. Such systems therefore make a sharp distinction between authors and readers. The concept of 'industrial strength hypermedia' is described as a goal to which system developers should strive but one that is a long way off. An industrial strength hypermedia system would allow collaborative authoring and linking between many different engineering applications such as CAD, databases, spreadsheets and analysis tools, through a link service. The use of a future industrial strength system is illustrated through a scenario in which an avionics design engineer uses a hypermedia project notebook which integrates project management, CAD and reliability analysis tools in a collaborative design environment.

A hypermedia working environment such as the one described could be seen as a very advanced form of groupware, but for such a system to have ‘industrial strength’ it would need many of the features of today’s document management systems such as concurrency control, access control and version control.

Despite the advantages of open hypermedia systems, it may be that a closed system is preferable in the maintenance environment, where most users may not need or appreciate the ability to create their own hyperlinks. The ability to update the information system with knowledge learned on the job would be a valuable feature however, if it could be carried out in a controlled manner.

3.12.2 Hypermedia on the shop floor

Many of the hypermedia systems described in the literature are integrated systems that cannot be described simply as training systems, operating manuals or diagnostic tools since they contain information that supports all three activities. This reflects the way that system authors have often tried to support work-based learning. The autoclave diagnostics system described by Bates (1991) is an example of this type of system.

Interactive task support systems are also integrated systems. Four types of support are needed for the shop floor environment, which requires an increasingly speedy response to problems and is becoming so complex that it may be beyond the cognitive limit of the unsupported mind (Kasvi *et al*, 1996). Bush (1945) also observed that man had “built a civilisation so complex that he needs to mechanize his record”.

Kasvi *et al* (1996) list the following criteria for ITSS usability:

- Learnability - users should be able to navigate the system after a 15-minute introduction and 30 minutes use.
- Efficiency - information searches should be faster and easier than manual paper searches.
- Memorability.
- Few errors.
- Subjectively pleasing - users should prefer the system to paper based instructions.

They also give further requirements such as the involvement of users in system design, the correspondence of the system structure with the mental models of users and that information content must be easy to create, update and maintain.

Koshy *et al* (1996) describe the use of hypermedia systems for training as well as preparation and presentation of computer-based manuals to support complex maintenance and calibration tasks. A closed hypermedia system manual was produced for the operation, calibration and maintenance of a complex balancing machine. The use of this hypermedia manual was compared to the use of an equivalent paper manual with the result that the hypermedia manual allowed greater performance and speed. Users clearly indicated their preference for the hypermedia manuals.

3.12.3 Hypermedia for training

Leung *et al* (1995) describe the development of a hypermedia quality manual and a hypermedia learning system for training users in ISO9000 concepts. The manual was authored initially using the Microsoft Windows help authoring tool, but the second implementation was produced using HTML for delivery over the WWW. The training manual was produced using a Windows hypermedia authoring tool. There is much duplication of material between the manual and the training package and since the common information was available digitally, material was simply copied from one application to the other during authoring. It is admitted that in the future, as these kinds of applications grow in size and complexity, the management of data integrity is going to become a much bigger problem, and it will be unwise to duplicate source material between information systems that complement each other. In the case of information systems for TQM it is clear that for large-scale systems, standards will need to be imposed to ensure data integrity. If the two hypermedia information systems described by Leung *et al* had been produced using an open hypermedia system such as Microcosm, there would have been no duplication since each system would have been constituted from the sum of all the source documents involved, using a separate linkbase.

Perhaps it should not be surprising that there should be such overlap between the training package and the manual described by Leung *et al* (1995) since both the EPSS and ITSS system concepts make little distinction between computer-based training and performance support. Hypermedia is used to supplement human memory in both cases.

Owen *et al* (1993) describe a hypermedia training system for use by operators, supervisors and maintainers at a water treatment plant. Two features of the system described are of particular interest here. One is the emphasis on animated sequences to explain the function of the plant as well as video clips. Both types of media require powerful hardware (by 1993 standards) to create and display the moving images but this is justified by claims for faster and more effective learning. The second novel feature is the provision of two alternative interface metaphors to guide users through the information. The authors provided both a textual user-interface based on existing paper manuals, which therefore uses a familiar book metaphor, as well as a graphical interface based on a process flow chart.

3.12.4 Hypertext and decision making

Because of the claimed similarity between the hypertext presentation of information and the way the mind processes such information (Shneiderman, 1989) much hypertext research focuses on the cognitive aspects of information use. An example of such work is a paper by Ramaparu (1996) which compares two methods of information presentation, sequential and hypertext from the point of view of their effect upon quality of decision making. He looks at the time to make a decision and the accuracy of the decision and concludes that matching the presentation of task information to the type of knowledge required for the task results in improved decision making. This result has important implications for decision support systems for maintenance.

3.12.5 Hypermedia diagnostic tools

Warren (1990) describes a maintenance information system for a chemical plant. A hypermedia tool is used to author and update a performance support system that is used by technicians responsible for the maintenance of process controllers. The performance support system uses a hypermedia approach to integrate information such as flow charts, part diagrams, animated sequences and procedure documents. Three issues are stressed, which are felt to be critical to the success of such a performance support system:

1. The information database must be complete in terms of diagrams, pictures, settings and procedures for every process controller used in the plant.
2. Complete training must accompany all information and procedures.
3. The controller technicians must be the primary authors and maintainers of the training/information system.

This last point is particularly important. It is argued that the only people who know whether the performance support system matches the real world or not are the technicians, so they must be given the authority to maintain the information system. This need not cause problems since it is felt that anybody who is capable of maintaining a process controller is capable of updating a hypermedia performance support system, providing that the authoring tool is user friendly, robust and bug-free. The authoring system described was usable by a technician after half an hour's training (Warren, 1990).

3.12.6 Hypermedia maintenance information systems

Shneiderman (1989) has proposed three rules to help identify suitable applications of hypertext. An application is suitable if:

1. A large body of information is organised into numerous fragments.
2. The fragments relate to each other.
3. The user needs only a small fraction at any time.

These rules would seem to describe a maintenance information system very well and several authors have described hypermedia applications for maintenance. As indicated by Crowder *et al* (1996) hypermedia is a natural method of structuring and delivering maintenance information for two main reasons:

1. Users require rapid access to accurate information, which is best provided by a system that matches the way the brain processes information.
2. Maintenance manuals are read in a highly non-linear fashion.

The systems described by Bates (1991), Koshy *et al* (1996), Torvinen and Milne (1996), Murray *et al* (1994) and Owen *et al* (1993) all use hypermedia information to assist maintenance.

Nelson and Smith (1990) compare the usability of paper manuals for the repair of mining equipment with their hypertext equivalent. They observe that most of the graphics, diagrams and text in the paper manuals were prepared on a computer and suggest that the change to digital manuals might therefore be relatively straightforward and inexpensive. Following their comparison of four repair manual formats for usability, they conclude that although users accessed the information more slowly using a computer, they preferred the hypertext presentation of maintenance information and this also enhanced their understanding of the information.

Wilson (1996) also identifies multimedia and hypermedia as promising technologies for enabling local control of manufacturing operations by shop floor workers, particularly in the field of maintenance. He also mentions several innovative user-interface technologies such as personal digital assistants, voice input and wearable computers that might further enhance the exchange of information with shop floor users. Wilson lists the following criteria for a maintenance information system that would support local users:

- Availability at site of maintenance.
- Flexible information detail and complexity according to user and task.
- Capability to provide graphical as well as alphanumeric information.
- On-line access to part stores, production records etc.
- Robustness, durability and preferably, portability.

3.13 Hypertext Usability

There is a strong body of literature on the ergonomics of human-computer interaction and some of this work has been described above. Traditional approaches often compare different information systems for speed and accuracy, and this type of study has been applied to studies of hypertext usability (Ramaparu, 1996). Other researchers such as Kasvi *et al* (1996) have tried to quantify parameters such as learnability, efficiency, memorability and whether a system is subjectively pleasing to use.

Smith (1996) suggests that hypertext is different from traditional information systems in that users can complain of feelings of 'lostness'. This is caused by the hypertext encouraging users to browse information to the extent that they forget where they started. Smith suggests methods of quantifying the degree of lostness as well as the confidence of users in their ability to find relevant information. This is done by analysing the path taken by users as they move from node to node through a web of hyperlinks.

When users have a choice whether to use an information system or not - as is usually the case with maintenance information systems - user acceptance of the system becomes an important issue. Davis (1993) uses the technology acceptance model (TAM) to investigate why system users accept or reject information technology. He shows that the TAM is a useful tool for acceptance testing and argues that as well as usability, system designers need to be very careful that their applications are perceived to be useful. The model hypothesises a causal relationship between user attitude and actual use. Attitude is in turn affected by both perceived ease of use and perceived usability which are both conditioned by the system's design features. In addition, the TAM postulates a causal link between perceived usefulness and perceived ease of use (Figure 3-5).

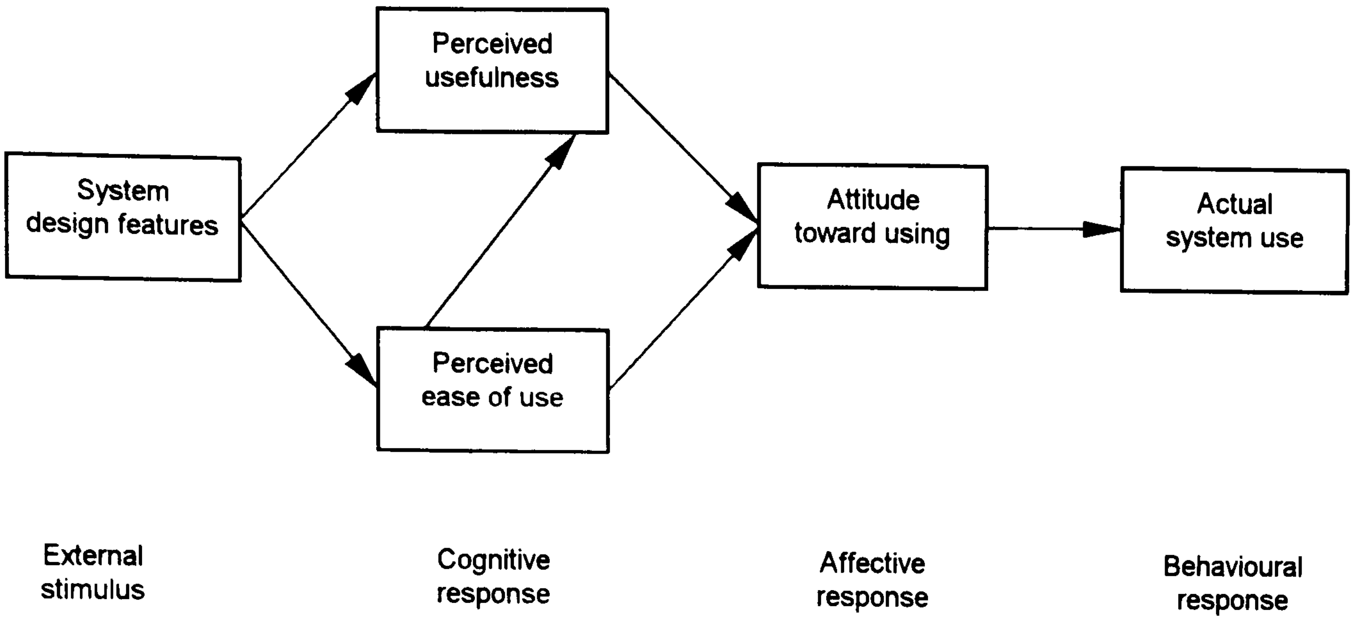


Figure 3-5 Technology Acceptance Model (source: Davis, 1993)

3.14 Document Management, PDM and EDM

The design and manufacturing processes for complex products can be greatly improved through the use of a document management system. Such is the complexity of the products of the aerospace industry that the number of documents generated during the product life cycle can run into the millions. Kane (1995) states that in such situations document management systems (DMS) can be very useful to speed document retrieval and apply the strict revision control that is necessary in this industry. She also indicates that such systems can assist in product maintenance by simplifying the preparation of maintenance manuals. As well as organising documents that are generated electronically, document management systems can incorporate legacy data that is scanned from microfilm or paper. The three core functions of a DMS are therefore:

1. Document management - the database within the DMS organises revision control, maintenance of an audit trail and the relationships between all documents and data.
2. Engineering workflow - this is used to manage the business processes used to generate, modify and use the information in the DMS. File management systems allow users to work on different parts of the same assembly or to collaborate on a design.
3. Document processing - a DMS must be able to read and manipulate documents in a wide range of formats. This may be achieved through the use of a neutral file format such as IGES, or by using a number of viewers for popular CAE and business software.

Document management systems are popular in many organisations that manage large volumes of live documentation as well as archives (such as local authorities), but when applied to an engineering organisation these information systems are often called engineering data management (EDM) or product data management (PDM) systems.

PDM is discussed by Bryan and Sackett (1997) who point out that as manufacturers have increased their product variety and shortened their product life-cycles, they have dramatically increased the complexity of their product data. The management of this data has become a constraint on further improvements in business performance. The authors list some benefits from case studies including a reduction in design-to-manufacture lead-time from 21 days to 6 days and a reduction in the cost of inventory of 50%.

Most users of PDM systems who use them to produce maintenance manuals will issue these manuals in paper form, but aircraft manufacturers are increasingly providing maintenance manuals in electronic form. British Airways Maintenance in Cardiff (BAMC) receive the content of their maintenance information from Boeing and they use their own document management system to produce paper manuals in a more usable form for their own technicians. A vice-president of the aircraft manufacturer Saab has stated the electronic documentation of aircraft maintenance procedures make their products easier to sell since their customers know that such information systems will reduce aircraft hangar time by 40% so that each aircraft earns correspondingly more revenue for the operator (Anon, 1997). The document management system at BAMC is described in appendix B.

The use of electronic manuals to assist maintenance began in the aerospace industry and is spreading to other sectors including the automotive sector (Keller, 1995). To date, product manufacturers have produced the most successful systems, which they intend that their customers should use to assist the maintenance of their products. One of the main obstacles to the provision of such a system for plant maintenance is the ownership of the documents to be included. Whereas operators of manufacturing systems can access their own *product* data with relative ease, the suppliers of their plant and equipment own the data describing their *processes*. Some of this 'process data' will be paper-based, and that which is in digital form will be available in a range of different formats. Nevertheless advances in scanning and document management technology have made possible the development of a 'process data management' system. The benefits of such a system to maintenance have yet to be demonstrated and this was one of the objectives of this thesis.

3.15 CALS

CALS is a strategic approach to PDM that was initiated by the US Department of Defense. CALS has come to mean various things including continuous acquisition and life-cycle support, computer aided logistics support and even commerce at light speed, but the approach generally involves the use of digital product data to reduce life-cycle costs. CALS has a high profile in manufacturing and the keynote speaker at the 1997 CALS Expo in Tokyo was the Chairman of Toyota, Mr Shoichiro Toyoda.

Although CALS is supported by the defence industry and driven by the military equipment procurement process, some of the elements of CALS are of more general benefit. Renishaw, a manufacturer of touch-trigger probes, has chosen elements of the CALS strategy to improve their business processes. An example of such improvements is a reduction in the time-to-market for Renishaw's new products from 2-3 years to 10 months (UKCIC, 1998).

3.15.1 Interactive electronic technical manuals

One of the elements of CALS that is of particular relevance to maintenance is the use of interactive electronic technical manuals (IETMs). Harris (1994) describes the provision of an 'expert maintenance advisor' (EMA) that was developed to support the US Navy's maintenance requirements and improve maintenance efficiency. Expert systems methods were used to create the EMA, which is used for training and performance support. One of the main benefits of the EMA to the Navy is the elimination of paper. The *USS Vincennes* stores 23.5 tons of paper above the main deck, which is more than its weapons load. The EMA takes a conventional expert systems approach in which the knowledge acquisition sessions are conducted with subject matter experts to embed maintenance hints for the system. There does not seem to be any provision for ownership of the knowledge base by the users, who treat the EMA as a training package that they cannot directly maintain. As well as being used in training, the EMA functions as a performance support system by supporting the basic functions of librarian, advisor and instructor. Another claimed benefit of the EMA is its ability to refresh users' knowledge which was gained initially through training and which may have become 'rusty' through lack of application. An IETM can be regarded as a special case of an electronic performance support system that is more closely specified by standards and is aimed at maintenance. An IETM might also be seen as a kind of memex (Bush, 1945).

3.15.2 Standards within CALS

There are many standards within CALS, but the 'umbrella' standard is MIL-STD-1840C, which covers the automated interchange of technical information. This standard also references many of the other CALS standards.

Many IETMs are produced in standard generalised markup language (SGML) which is a superset of hypertext markup language (HTML) and has many advantages for hypermedia authors. Landis and Horton (1996) describe the use of SGML documentation in the C-130 aircraft programme and they explain the advantages of this approach for the production of IETMs. Griffiths (1998) briefly explains the many electronic document standards available nowadays including SGML, HTML and PDF. Whereas HTML requires an author to markup the source document by embedding tags in the text, SGML tags are stored separately. SGML removes the formatting from a document so that only the content is preserved. As with HTML formatting is applied only when the document is read which makes both HTML and SGML documents independent of hardware and software vendors. Despite these advantages, SGML has considerable disadvantages for smaller organisations in that it requires expensive authoring software and hardware as well as specialist training for authors. Although HTML authors have little control over the appearance of their documents when read (this being a function of the web browser used), there is far more control with SGML. Griffiths illustrates many of the common formats in terms of their stored intelligence (Figure 3-6).

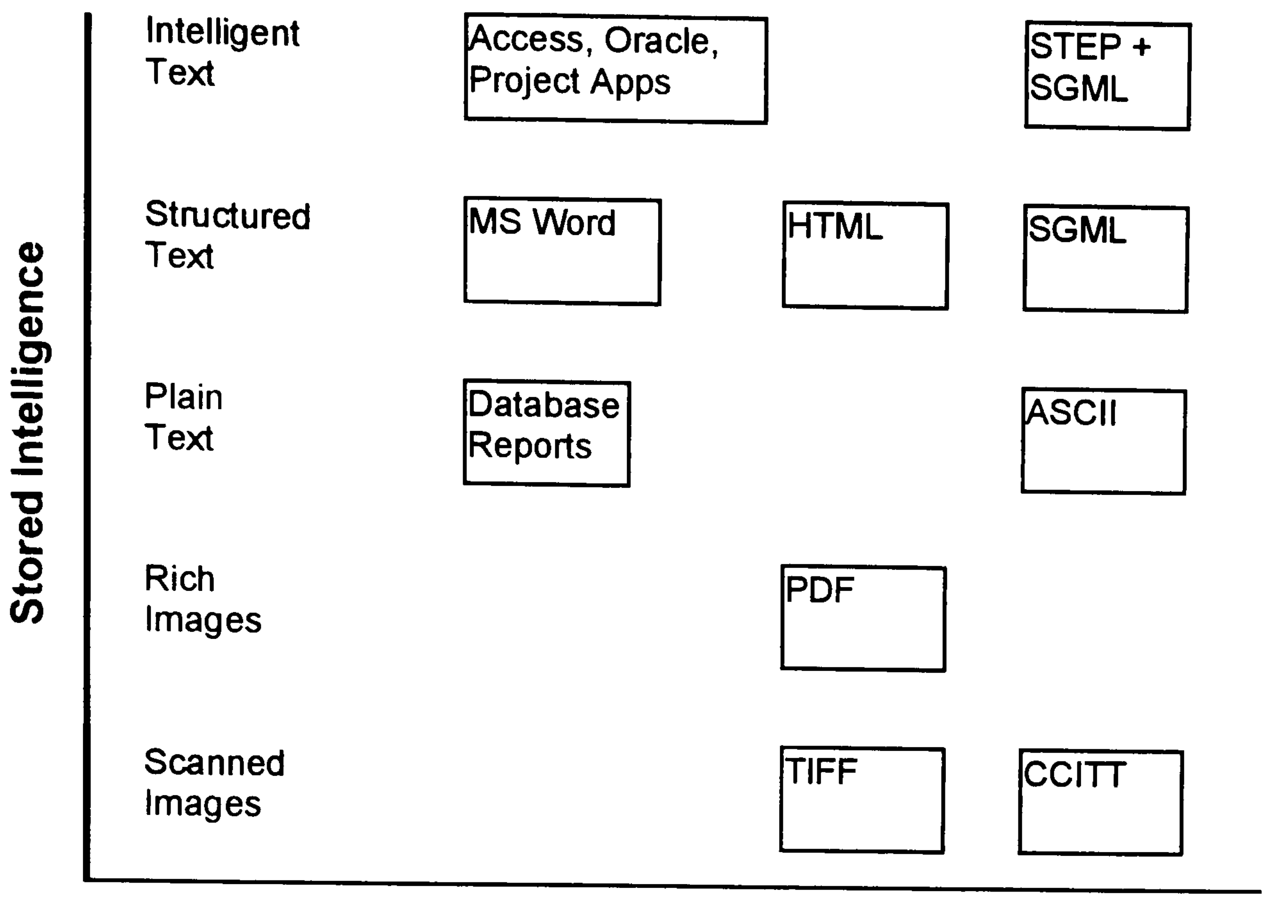


Figure 3-6 Textual Information and Intelligent Access
(source: Griffiths, 1988)

3.15.3 CALS and PDF

The portable document format (PDF) standard from Adobe Systems once presented a dilemma for document managers since although it was very popular for its convenience and ubiquity, it was and still is a proprietary standard. This is no longer a problem since the CALS community has accepted PDF as a data standard. MIL-STD-1840C describes data formats for storing compiled page layouts in electronic form and one of the two standards mentioned here is PDF (Griffiths, 1998).

3.16 Summary of Chapter

This chapter considered the human-centred approach to information systems and how this might be applied to maintenance. The reason for this is that successful TPM programmes are driven by people rather than technology. Many prize winning TPM users do not operate a CMMS but nevertheless take a very systematic approach to maintenance. This does not mean that computers are irrelevant to TPM, merely that a different approach may be needed. It is suggested in chapter 3 that a human-centred approach may be more appropriate. Several approaches to the design of human-centred information systems have been described including methods based on the socio-technical systems approach to organisational redesign. The reason for this is that TPM is a team-based approach to maintenance. The different levels at which users interact with computers have been discussed since system usability is a critical factor in the success of an information system.

Since much research into diagnostic maintenance systems features artificial intelligence, this subject has been covered briefly. However since the pure AI approach is somewhat at variance with the human-centred systems approach essential for TPM, some researchers have tried to blend these two types of system designs. Examples of such research have been described.

Information technology has also been applied to the development of an organisational memory - a kind of computerised kaizen. The subject of knowledge management was introduced briefly before looking at how hypermedia systems may be a natural approach to such information systems due to the associative structure of hypermedia information. Static hypermedia systems such as digital manuals have been covered as well as more dynamic hypermedia systems that allow users to update the knowledge contained in the system.

4. Development of Hypothesis and Methodology

This chapter summarises the results of the literature review described in chapters 2 and 3 and uses these to formulate both a hypothesis and a research methodology.

4.1 Digital Manuals for Maintenance

In chapter 2 it was shown that many innovations in maintenance were developed to enhance the support of defence systems and civil aircraft. A recent example of one such innovation is the interactive electronic technical manual (Harris, 1994). These are digital documents comprising text, drawings and pictures. They are usually hyperlinked, in which case they represent examples of hypermedia information systems. The potential downtime savings to be made have justified the high cost of production of these manuals. Aircraft operators find the cost of maintenance to be a very high proportion of total operating cost. Aircraft manufacturers also find the cost of manufacturing system maintenance to be a very high proportion of total manufacturing cost.

Another industry where the cost of downtime can be very high is the automotive manufacturing industry, particularly where automated systems such as FMS and transfer lines are used. The importance of the human element in the maintenance of such systems has recently become more widely understood by Western manufacturers, many of whom have adopted a human-centred approach to maintenance that is called total productive maintenance (TPM). The literature reviewed in chapter 2 suggests that the development and use of an IETM might be a suitable complement to TPM, where this is practised. Chapter 2 also shows that while many organisations use the analytical power of the computer to improve the *management* of their maintenance activities, this approach is less relevant to the *execution* of maintenance in the factory. Organisations have also been criticised for not taking a strategic view of their maintenance activities before installing such systems, and for failing to consider adequately the people issues involved in their use. The results of these mistakes are high levels of dissatisfaction with CMMS and low levels of system usage among shop floor workers (Jones, 1994; Swanson, 1997).

4.2 Artificial Intelligence and Maintenance

Where computers have been applied to the execution of maintenance (as distinct from the management of maintenance) a common approach has been the application of artificial intelligence (AI), which is used to assist fault diagnosis (Turban and Aronson, 1998). Although such systems have been shown to be of benefit in medical diagnosis, when applied to manufacturing systems, a fundamental problem is the incomplete knowledge of possible failure modes. Although knowledge-based systems (KBS) have been used successfully to assist the maintenance process, they are unlikely to replace skilled knowledgeable humans who can deal more rapidly and effectively with unforeseen failures. Too often, the AI and KBS approaches to maintenance are technology-centred rather than human-centred. However there does seem to be scope for the successful integration of expert systems and multimedia information systems. The main difference between this and the traditional AI approach is the use of a multimedia user-interface to elicit knowledge from experienced users during the life cycle of the information system. This contrasts with the elicitation of knowledge from an expert, which is part of the development of a conventional KBS. In the multimedia-enhanced expert system, as users learn about the assets for which they are responsible they update the system with their knowledge by reporting failures and documenting their solution. This knowledge is then made available through the expert system to other users. Such a system can clearly be used to support team-based maintenance, subject to the validation of updates to the knowledge base by a recognised authority, such as the team facilitator.

4.3 A Generic Digital Manual for Manufacturing

The multimedia or hypermedia parts of the systems described above sometimes take the form of an IETM, but where this has been done the resulting systems have always been designed for a particular organisation or industry. There is scope for the development of a generic approach to the use of IETM technology in manufacturing systems maintenance. Since IETMs are designed to be used by those who might not normally use an information system, the design of the user-interface is particularly important. Much research has been done into the design of human-centred information systems for manufacturing, particularly on the user-interface. Chapter 3 surveys such work in order to inform the development of an IETM for manufacturing systems maintenance.

Much research has been carried out to identify the factors that contribute to the successful implementation of IT in manufacturing. A common finding is that system developers often do not take sufficient account of the social and cultural environment in which information systems are used. The users of most current IETMs are either those who service military equipment or the operators of commercial aircraft. Clearly the social and cultural environment in which these IETMs are used is different from that found in most factories. The success of IETMs where they have so far been used does not necessarily indicate that such systems will succeed in the factory. In addition, the development of an IETM to support a manufacturing process might be expected to differ from the development of a similar system to support a product (whether the product is a warship, airliner or car). The manufacturers of a product are also the originators and owners of the information such as drawings, sketches, photographs and text, which is used to describe their product. The users of a process will probably not own the information used to describe that process, and they must therefore collect the media they might wish to include in an IETM. These media will exist in a range of different forms, some digital (in various formats) and some on paper or film. The production cost of a product IETM can be recovered through the cost price of many products, the marketing of which may be enhanced by the IETM. The cost of producing an IETM to support a single process must be recovered through reductions in downtime, more effective planned maintenance, improved training and other such benefits.

4.4 Human-Computer Interaction and Hypermedia

As a result of the cost of failed IT programmes, there has been and continues to be a considerable amount of research into human-computer interaction. Many information systems, including electronic performance support systems (Gery, 1995) and interactive task support systems (Kasvi *et al*, 1996) are designed to support workers in the performance of their primary tasks. Such systems often feature hypermedia as a means of delivering information to the user. Where systems designers have focused on support for manufacturing systems maintenance, it has been shown that there are several characteristics of successful systems:

- They do not constrain users unduly (Eason, 1991)
- They allow organisations to leverage the 'tacit knowledge' of their workers (Karwowski *et al*, 1994).
- They do not take longer to author than an equivalent paper system (Eloranta *et al*, 1995).
- They are user friendly and flexible (Vanneste and van Wassenhove, 1995).
- They must be aligned with the maintenance strategy adopted by the organisation, in this case TPM (Jones, 1994).
- They should be compatible with developments in user-interface technology such as voice input, touch screens and portable computing (Eloranta *et al*, 1995; Wilson, 1996).
- They should allow different users (perhaps different types of user) to access the information in the system rapidly and in the manner most appropriate for them. Many authors (e.g. Crowder *et al*, 1996) suggest that this is best achieved by using hypermedia.
- They provide information at the site of maintenance. This might be achieved via a network or by using portable computers (Wilson, 1996).
- They should give access to part stores, production records etc. (Wilson, 1996).
- As with any such technology, it must be acceptable to a manufacturing organisation and be shown to have quantifiable commercial benefits.

4.5 Hypothesis

The aim of the research described in this thesis is to generate knowledge that will assist developers to provide this type of ideal information system in the future. It is now possible to state the hypothesis that is tested by this research as follows:

A human-centred information system using hypermedia is an effective means of supporting total productive maintenance.

4.6 Research Methodology

Many of the features of the type of information system suggested in the hypothesis are present in the hypermedia system developed for Pirelli Cables by Crowder *et al* (1996). The main differences between the proposed system and the Pirelli system are consequences of the different industrial environment at Ford, where TPM is practised. Because of the requirement to align the proposed system with the maintenance strategy adopted by the sponsor, the implementation of a hypermedia system to support TPM will be different from that described by Crowder *et al*.

4.6.1 The ideal methodology

An ideal methodology would be to develop a pilot hypermedia information system that could be used exactly as a full system would be. This pilot system would then be studied to allow any benefits to be evaluated. Such a system would be closely integrated with other sources of relevant information at the test site (such as the spares inventory management system) and would present all the maintenance information required by each different user in a form most suitable for that user. The development of the user-interface and the hyperlinking strategy would be carried out with the full involvement of all users and the resulting system would be used during a full range of maintenance activities before evaluation by all workers and staff in the area involved with the pilot. However, this methodology is impractical for two main reasons:

1. The practical difficulty of developing a fully integrated hypermedia system within the limited scope of a research project.
2. The limited degree of user involvement possible during development of the system.

Although Wilson (1996) advocates on-line access to information such as spare part inventory levels, this was felt to be a practical impossibility for this type of project in an organisation like Ford. The view was taken that since the assembly line was a mature installation, information such as part drawings and stores numbers could be regarded as static. A more dynamic type of data that is relevant to maintenance is breakdown data, but since Ford had mechanisms in place for the collection of such data, it was felt that this function was of secondary importance compared to the use of hypermedia to present usable information. Although an ideal hypermedia information system would allow both user input and the display of dynamic data, a static approach was considered to be acceptable for this project.

The main reason for the lower than ideal level of user involvement was that many of the users for whom the system was designed are assembly line workers, whose job makes them 'line-tied'. They could not afford significant time away from the assembly line, which meant that the researcher had to take whatever opportunities arose to gather feedback from users. In any case the value of high levels of user involvement could be questioned due to the lack of user expertise. This is recognised as a common problem in the development of information systems (Wong and Tate, 1994; Clegg *et al*, 1997) and was compounded in this case by the novelty of the proposed information system and the relative inexperience of the researcher. Users could not be expected to understand fully the limitations and possibilities of today's hypermedia information systems. It was expected that users would disagree with each other when criticising the prototype system since they have different sets of skills and levels of skill. Since the author is a manufacturing engineer rather than a computer scientist, it was hoped that his own interests in maintenance and usability of information rather than technical sophistication might lead to a degree of empathy with users and simplify discussions with them.

Although the sponsoring company was using TPM during the entire project, no CMMS was in use on the Zetec assembly line. One was planned for introduction here, but this had not taken place by the end of the project.

4.6.2 The methodology chosen

Because of the constraints described above, the following methodology was chosen to investigate the hypothesis:

1. Confirm the suitability of Microcosm.
2. Investigate user requirements with teams at sponsor's site.
3. Develop a pilot hypermedia information system to support team-based maintenance of a manufacturing process at the sponsor's site.
4. Demonstrate the system to users in maintenance teams at the sponsor's site to evaluate and record their reactions to the system after each iteration of the design cycle.
5. Develop the system further based on user feedback. Leave a copy of each version of the system at the sponsor's site for users to evaluate in their own time.
6. Test system usability according to the Technology Acceptance Model (Davis, 1993).
7. Quantify cost benefits.
8. Test for applicability to team-based maintenance outside Ford and motor industry.

Chapter 3 has shown that Microcosm is the only commercial open hypermedia system which has 'industrial strength' (Crowder *et al*, 1996). An open system was considered essential since maintenance information exists in a range of formats and it was considered important not to alter the source documents. Microcosm offers a unique feature, which is the creation of 'linkbases' that are separate from the media used. These linkbases can be identified with particular users or classes of user, which was felt to be a very useful feature for a system suitable for team workers with different trades and levels of skill. An 'industrial strength' system was considered to be important for the factory environment where hypermedia is still relatively uncommon. It was still necessary to confirm the suitability of Microcosm. This was to be done through a presentation to those involved at Bridgend, a visit to Pirelli Cables and discussions with the suppliers of Microcosm, Dr Crowder and the multimedia research group at Southampton University.

Due to the inexperience of users, it was felt that a user requirements specification would be impossible to produce and a combination of presentations and discussions would best enable the first prototype system to be developed. Thereafter, the design process would be an iterative one with each new prototype system being developed in response to the reactions of users to the last system. The choice of pilot area was to be decided through discussions with team members and the maintenance co-ordinator.

The development of the pilot system would include collection of all the media to be used. This task has been estimated by Crowder *et al* (1996) to constitute 80% of the time to produce a hypermedia information system. The ideal pilot system should have the features identified in paragraph 4.4 above. On-line access to the stores database would not be provided since this would have required an interface to Ford's information systems, which is beyond the scope of this project.

Following discussions with the sponsor, it was felt that benefits would be derived through reductions in downtime. It was therefore necessary to start recording downtime without the hypermedia system so that when it became available it would be possible to compare downtime and evaluate any differences.

The test for applicability outside Ford would be achieved through semi-structured interviews with individuals who are believed to have detailed knowledge of team-based maintenance.

4.6.3 Changes to the methodology during the project

The development process commenced according to the research methodology described above, but during the research two difficulties were encountered that resulted in changes to the methodology:

1. It was impossible to deliver a robust system that was suitable for the factory environment at Bridgend using Microcosm. A more robust hypermedia tool was adopted but since this did not allow the development of a truly open hypermedia system, some of the most important benefits of Microcosm became unavailable. It was therefore impossible to research the use of different linkbases that are separate from the media. The research now focused on the use of a more limited type of hypermedia information system in a team-based maintenance environment.
2. For technical reasons it was not possible to accurately record the downtime on the pilot assembly machine. For each breakdown and minor stoppage, the machine controller records the time that the machine stopped. However, this time is lost when the controller is reset to bring the machine back on line. A request was made to record these times before resetting the controller and this was sometimes done, but the figures could not be used with any degree of certainty. In the end, conservative estimates of downtime were used, based on experience. Since the main purpose of a cost benefit analysis was to indicate whether the sponsor company should proceed with the development of hypermedia maintenance information or not, accuracy was not considered essential as long as the calculations were based on conservative estimates.

4.7 Summary of Chapter

This chapter has stated the research hypothesis and the methodology by which the hypothesis was investigated. An ideal methodology was postulated but for practical reasons this could not be used. A more practical methodology was then described in detail. During the development process (which is described in detail in the next chapter) it was discovered that even the more practical research methodology could not be followed exactly. The research therefore deviated from the stated methodology, although the hypothesis can still be tested.

Chapter 5 describes steps 1, 2, 3 and 5 of the methodology, which are the identification of a suitable hypermedia authoring system, the investigation of user requirements and the development of the system. System development was an iterative process since each after stage of development, the system was demonstrated to users to collect their feedback (step 4 of the methodology) and allow further development.

Steps 6, 7 and 8 of the methodology are covered in chapter 6, which describes the evaluation of the pilot system.

5. Development of Pilot System

Ford's Bridgend Engine Plant was chosen as a test site for the pilot information system following a study by the researcher of the use of teamworking on the Zetec assembly line (Greenough, 1998). The researcher became familiar with the work force on part of this line and some of the maintenance problems in the factory. Permission was given to develop and evaluate an information systems approach to solving some of these problems. This chapter describes firstly the industrial environment in which the development took place and secondly the stages in the development of the pilot system, in chronological order.

5.1 Maintenance at the Bridgend Engine Plant

Ford's engine plant in Bridgend, South Wales was built in 1978 and now manufactures several variants of the Zetec and Zetec SE engines, the connecting rods for a range of diesel engines and all variants of the Jaguar AJV8 engine. Engine manufacturing involves machining processes and assembly processes.

5.1.1 Machining and assembly lines

Machining takes place on automated transfer lines that convert material from raw castings to finished, machined items. Assembly processes are arranged slightly differently since the material is carried along a series of inter-connected loops. Each loop is a powered conveyor with a number of pallets designed to hold components or assemblies. At certain points along the main assembly loop, engines are tested to ensure correct assembly, and if an engine fails a test it is diverted into one of a set of 'repair loops' for manual rectification. Assembly processes may be automated (e.g. cam belt tensioning) or manual (e.g. inlet manifold assembly).

5.1.2 The Zetec assembly line

The Zetec assembly line is made up of three interconnected lines, the petrol hot test cells and the after test engine dressing operations in which components such as the clutch, exhaust manifold and belt covers are added. The assembly lines themselves are called the A line, the head line and the B line. The A and B lines are divided into several smaller areas, each of which is manned by a team of workers on each shift. The A line assembles pistons, connecting rods and cranks to the cast iron block after which the oil pan and several ancillary items are attached.

In future Ford's new global CMMS will be extended to cover Zetec assembly, but in the mean time maintenance is managed as described below.

5.1.3 Planned maintenance on Zetec assembly

There are several approaches to planned maintenance on the Zetec assembly line depending on the size of the task involved. Major refits and refurbishment are carried out during the summer shut down period and other planned maintenance activities usually take place during the weekend maintenance shift. An exception to this is the upgrade to the piston to connecting rod assembly machine that took place over the 97/98 Christmas break. In this case, the build schedule was altered to allow a stock of engines to be assembled before the old machine was removed. Some planned maintenance may be undertaken on an opportunistic basis, for example if there are component shortages.

The work content of planned maintenance is held in the scheduled maintenance system (SMS) that prints work orders on special forms according to the maintenance schedule. The content and frequency of SMS tasks is under the control of the maintenance co-ordinator for Zetec assembly. Each SMS form has a detachable lower portion that allows maintenance workers to feed information back to the maintenance co-ordinator.

5.1.4 Unplanned maintenance on Zetec assembly

Before teamworking, Ford production workers requested unplanned maintenance work via a maintenance request form (MRF). These were filled in by hand and the data entered into a computer by clerical workers known as 'coders'. Production workers would often be idle whilst the maintenance work was carried out. Under teamworking the use of these forms was discontinued. Maintenance work is now often requested verbally and carried out within the team. It is felt by Ford staff that teamworking has greatly reduced response time and downtime, however it has denied the company a detailed written record of requests for unplanned maintenance work. This record may be provided in future by electronic diagnostic systems similar to those currently installed on machining lines.

The detachable portion of an SMS form may be used to request unplanned maintenance work, and the information on these forms may be copied onto MRF forms to be entered as before, but most work of this type is not recorded in any formal way. The planned introduction of TEM will allow recording and analysis of downtime data, which can be used to improve reliability.

5.1.5 Data collection to calculate OEE

With the introduction of FTPM, it became necessary to collect data to derive the overall equipment effectiveness of certain machines. At Bridgend, bubble cards (see Figure 5-1) are used to code reasons for stoppages, duration of stoppage etc. Each line worker has a set of these cards and a list of associated fault codes. At the end of a shift, the cards are collected and each week they are fed into an optical mark reader that sends the data to a spreadsheet to calculate the OEE. The bubble card system is usually used on key machines that are the subject of a fault finding investigation. It is recognised that manual data collection of this type will tend to give lower downtime figures than the true level. It is therefore planned to extend the current ANDON board system to record the total time that each operation was out of cycle. The ANDON boards are operated by a signal from each PLC on the assembly line so that they display any operation that has dropped out of normal automatic operation, and alert plant operators and supervisors to the fact.

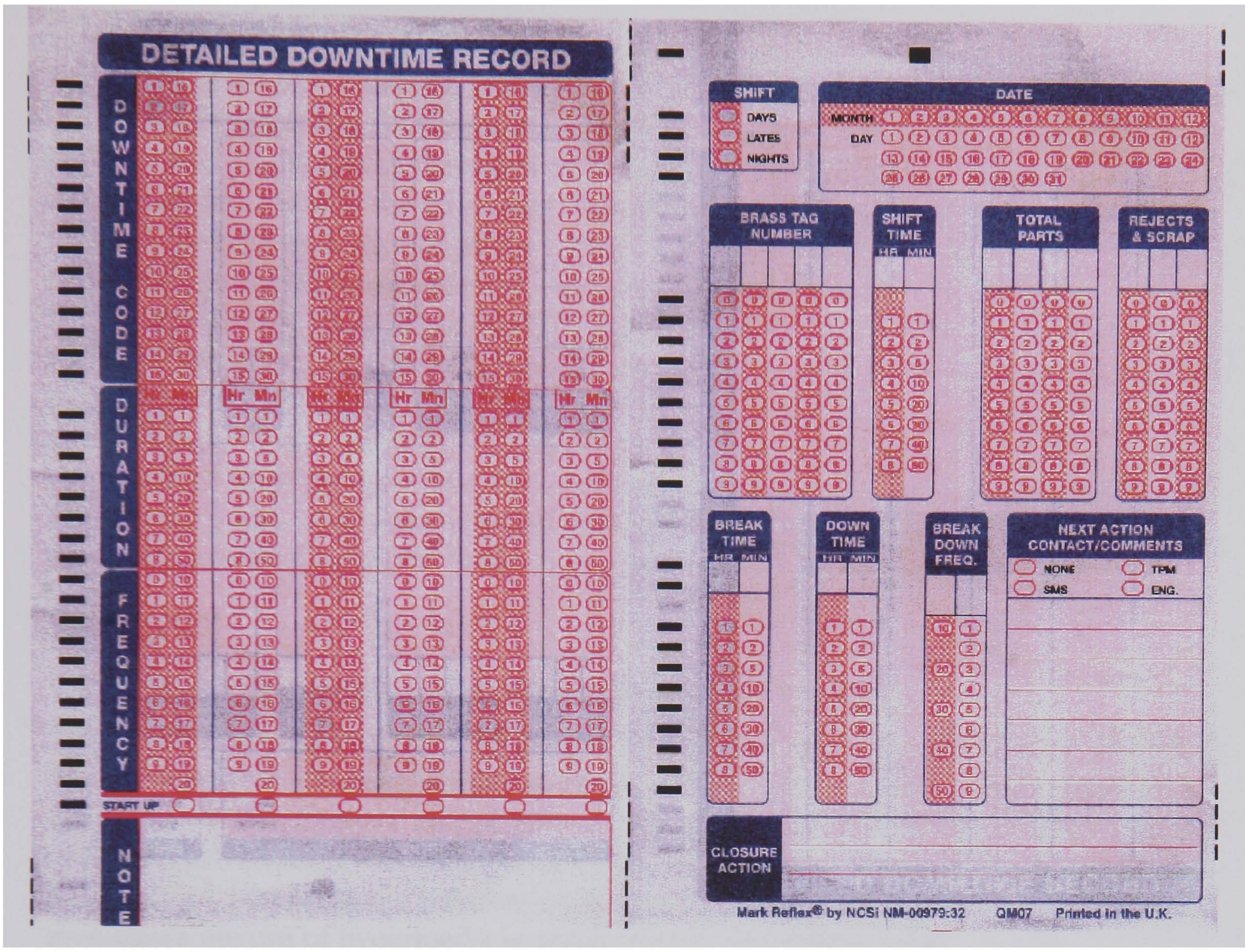


Figure 5-1 Bubble cards for OEE data collection

5.1.6 Spares inventory control

The control of spare part inventories is carried out by the stores system used for production items that is called MatLoc. This is a text-based system that is very unpopular with factory workers due to its poor user-interface. Many users complain that they actually preferred the older system (also text based) since it was felt to be more user-friendly. The use of MatLoc is time consuming but fairly straightforward for an experienced skilled worker. However it is considered extremely tedious by most team members who tend to leave it to the skilled workers or the maintenance co-ordinator. The result is that many of the benefits of teamworking are not realised due to the use of inappropriate information systems.

In some cases, for example if the reference number on the aperture card is illegible, it may not be possible to identify a spare part from the drawing. In this case, the component must be identified from the label on the faulty component (if this is visible and legible). This might involve removal of the old component, which obviously requires that the machine be stopped until a replacement part can be found.

5.1.7 Maintenance information

As well as spare part numbers, much of the information needed during maintenance is in the form of engineering drawings, manufacturer's manuals and supplier catalogues. The experience of maintenance managers at Bridgend is that a significant (but not quantified) element of downtime is the time spent searching for information. This information might relate to the correct operation of the system, the Ford reference numbers for a spare part, its location in the stores or the manufacturer's reference number. Much of this information is held on engineering drawings of which there are over 35,000 for the Zetec assembly line alone. The drawings are stored as 35mm aperture cards and several sets are available on the shop floor. Ford has recently installed a document management system called 'Image' that is intended to improve access to engineering drawings. Many thousands of drawings have been scanned and archived in the Image system. Image does not contain pages from vendor catalogues and is not a hypermedia system. It is a stand alone information system that is not integrated with the stores system or Ford's new CMMS.

5.2 Design Process for the Pilot Information System

The benefits of a hypermedia maintenance information system (as described in chapter 2) were presented to the maintenance co-ordinator for Zetec assembly. He confirmed that this approach was likely to enable reductions in downtime, and for this reason no formal requirement definition was undertaken before the design commenced. It was agreed to develop a pilot hypermedia information system that could be used as a research tool to investigate the use of hypermedia to assist team-based maintenance.

5.2.1 Scope of pilot system

The pilot system was not intended to carry out the functions of a CMMS since it was known that TEM would eventually fulfil this role, and it was not intended to be integrated with any Ford systems since it was felt that this would slow the development process unnecessarily. However, if successful it was envisaged that the pilot system would be used to inform the development of future versions of TEM that would either replace or interface with all relevant information systems.

The main objective for the pilot information system was to improve the speed and quality of information access since it was felt that this was one means by which significant downtime savings could be made. As a research tool, the information system was intended to allow an evaluation of hypermedia as a means to facilitate users' understanding and maintenance of a complex machine. As a pilot system, the information contained refers not to all machines along the assembly line, but to one particular machine in the A1 area.

Hypermedia systems are a relatively new type of information system for which formal design tools are in their infancy. The overall design process was as follows:

1. Identify pilot assembly machine.
2. Identify suitable authoring software.
3. Collect and create media to be included in pilot system, reformatting where necessary.

4. Design a pilot hypermedia information system using a structured design methodology (Isakowitz *et al*, 1995).
5. Evaluate pilot system with users and other relevant parties, recording results of each evaluation.
6. Repeat steps 4 and 5 until system fulfils requirements described in chapter 4.

5.3 Identification of Pilot Assembly Machine

The assembly of Zetec pistons to connecting rods is a fully automated process known as operation 110. The assembly process involves heating the little end to allow the gudgeon pin to pass through it during assembly, before a jet of cold air shrinks the little end onto the pin. Heating is achieved by placing the rods in an inductive heater before quickly assembling them to the pistons. For this reason the operation cannot be performed manually, so it is very important that there are no unplanned stoppages of the assembly machine. If such a stoppage does occur and is not quickly rectified, the rest of the assembly line would stop within a few minutes. Fortunately operation 110 is very reliable, but it is the bottleneck for the assembly line, which makes timely maintenance critical. It was felt that if hypermedia were of benefit anywhere, it would be so here.

5.3.1 Assembly machine

The piston to connecting rod assembly machine was replaced during the course of this project to accommodate new engine variants, but the principles of the new machine are similar to the old one. The new machine is illustrated in Figure 5-2.

5.4 Choice of Hypermedia Authoring Software

The development of a hypermedia maintenance information system is described by Crowder *et al* (1996) who applied it to the maintenance of a machine used by Pirelli Cables. This application was authored using an open hypermedia tool called Microcosm that was developed by the Multimedia Research Group (MMRG) at Southampton University. Microcosm is now sold by a commercial venture called Multicosm.

The identification of a suitable authoring system for the Bridgend pilot was not an exhaustive procedure since it was the use of hypermedia in a team-based maintenance environment that was to be tested, not the authoring system itself. However it was important to ensure that the authoring system chosen could actually produce the type of hypermedia system required.

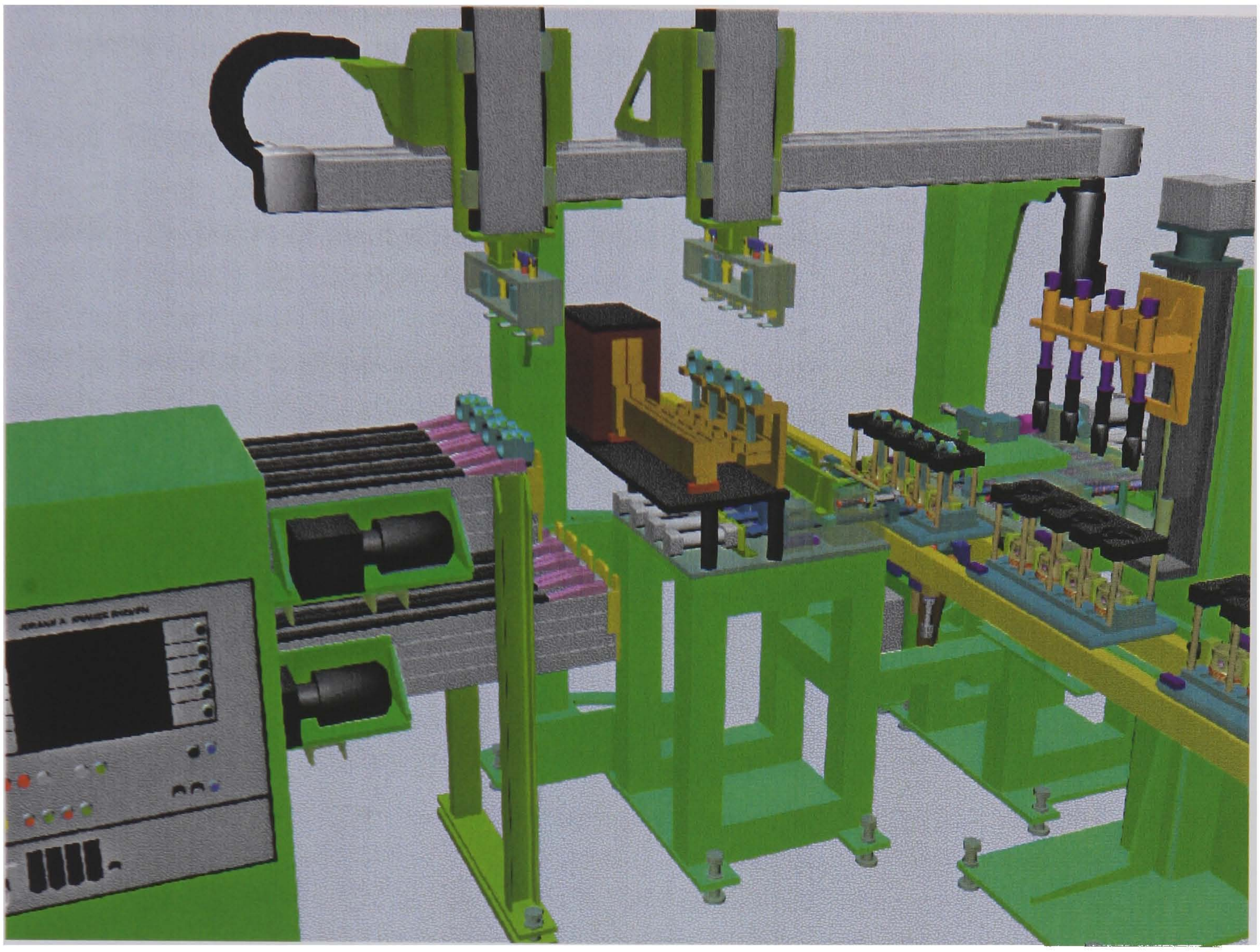


Figure 5-2 Piston to connecting rod assembly machine

5.4.1 Demonstration of Microcosm at Bridgend

Before development of the first pilot applications started, Dr Crowder from the Multimedia Research Group at Southampton University presented Microcosm and the concept of hypermedia to the managers and team members responsible for the section of the assembly line concerned. Following the presentation and during the development of the first applications, the concept of hypermedia and its possible use in maintenance were discussed with the maintenance co-ordinator and team members. The most important benefit was felt by the co-ordinator to be rapid identification of part details in the case of breakdown maintenance, leading to shorter breakdowns.

5.4.2 Example of typical breakdown

The maintenance co-ordinator gave an example of a failed axis drive motor. He had logged onto the stores information system (MatLoc) in order to identify a spare part, but when he looked at the machine in the factory he found that the part reference number was incorrect. Since he could not log onto MatLoc at two terminals at the same time, he had to go back to his office and either log off and return to the factory, or try to remember the details from the shop floor and type in the new part number. During all this time, the line had stopped. It was pointed out that it is much harder to identify correct parts at night when the co-ordinator is not at the factory. In his view, the availability of all relevant information right next to the machine could dramatically reduce downtime.

5.4.3 Design intent

The manager of the Zetec assembly line asked if the hypermedia system could be used to indicate the intent of the designer of the assembly machine. This information could be very valuable if, for example, modifications were found to be necessary. It was felt that although the design intent would indeed be valuable information for inclusion, it should be captured and recorded during the design process itself. This was felt to be beyond the scope of this project.

5.4.4 Other perceived benefits

The use of hypermedia to identify a spare part could save much time compared to the conventional text based search of a spare part database. The reason for this is that the text search depends to some extent upon the words and phrases used by the person who entered the data. The example given was the difficulty in identifying *valve, non-return* if the database contained the name *non-return valve*. It was accepted that this problem did not require hypermedia as a solution, merely a better database search facility.

The demonstration of Microcosm featured an example of electrical maintenance at Pirelli and the use of a similar system at Bridgend for electrical and hydraulic diagnostics was considered. However, it was felt that a hypermedia information system for electrical maintenance would offer few diagnostic benefits at Bridgend unless it was linked to the controllers for the automated devices used on the line. An on-line diagnostic system could be very useful if it displayed the logical state of all control signals clearly and in real time. This was felt to be beyond the scope of this project since it had little relevance to most team members.

It was felt that hypermedia could be very useful in planned maintenance as a replacement for the procedures guide. An example might be the presentation of the torque settings for all bolts in a clear fashion. It was decided to produce a pilot application describing the belt changing procedures for the Bosch drive belts used in Operation 110.

Team members also identified many other potential applications of hypermedia in maintenance such as:

- A set-up procedure for the drive system encoders.
- The presentation of secondary information about spare parts such as manufacturer's part number, type, specification, installation instructions etc.
- The training of new team members or the familiarisation of all users with a new line and/or operation.
- The use of the animated sequences when discussing complex machine movements in a meeting.

In the opinion of the team members, there are few things more useless than an obsolete spare part catalogue. They recognised that the information in the hypermedia system would have to be maintained by somebody.

5.4.5 Visit to Pirelli Cables

Following the demonstration of Microcosm, a visit was arranged to Pirelli Cables to see the use of Microcosm, and discuss its application to the Ford maintenance problem. As with the proposed Ford system, the Pirelli application was a pilot system intended to demonstrate the use of hypermedia information on a particular machine. Pirelli intended to use the pilot system to help them troubleshoot the electrical and electronic systems inside the controller of one of their domestic wire packaging machines. If this type of control system were designed today it would be based on a PLC, but the system on the old machine featured discrete logic elements in a very complex circuit. It was difficult to follow connections in the circuit using paper drawings, but the use of hypertext links between digital drawings made it much simpler. The circuit diagrams are mostly scanned bitmaps, which made authoring very time consuming. Some diagrams had been re-drawn using AutoCAD and this allowed Microcosm to make hyperlinks automatically to components using the block name of the associated symbol as a link anchor. To do this, the development team had had to write a special viewer for drawings that were stored in Autodesk's DXF format. The hardware used for the Pirelli application was a portable pen-based PC that allowed users to view electrical diagrams right inside the control cabinet. However due to fear of pilfering, the PC was locked in a cupboard until requested for a maintenance or training task. The visit to Pirelli showed that Microcosm seemed to fulfil those features identified by Wilson (1996) which were considered essential at Ford. The ability of Microcosm to present information according to user or task by identifying different users or groups of users with individual linkbases was shown to be particularly powerful.

Pirelli could not show objectively that the hypermedia approach had improved their maintenance since they did not keep detailed downtime records before they introduced Microcosm. They use the system for training as well as trouble shooting. Pirelli use a CMMS to measure the performance of their maintenance function

5.5 Collection and Creation of Media

The media that were chosen for inclusion in the pilot system were those that were felt useful for the maintenance tasks already carried out, as well as those that might be useful in the future. The media were:

- Engineering drawings ranging in size from A0 to A4.
- Still pictures in the form of scanned pages from vendor catalogues, digital photographs and rendered images of parts of the machine.
- Text in the form of lists of spare parts with their associated numbers and stores reference numbers.
- Animated sequences that were used to describe the operations of the various parts of the machine.

5.5.1 Large Format Engineering Drawings

The inclusion of engineering drawings was felt to be fundamental to the success of the hypermedia system. Maintenance team members use drawings both to understand the operation of parts of the machine and also to identify components to be replaced or repaired. Initially, only drawings of mechanical parts of the machine were to be used although electrical, electronic, hydraulic and pneumatic drawings were also available. This was because mechanical drawings were felt to be of relevance to all members of the teams, for identification of spare parts and to explain the function of the machine. The other drawings tended to be used by the skilled workers only.

The most natural way to study an engineering drawing is to view the paper original or if drawn using CAD, to print the original. Storage of large numbers of paper drawings is expensive and they are vulnerable to damage so they are usually either stored centrally and copied when required, photographed and stored on aperture cards or scanned and stored digitally. If a full-sized paper drawing is not available, optical or electronic viewers are used and these must allow users to zoom into and pan around a drawing. The ease and speed with which this is possible is a very important factor in the usability of an imaging system.

The drawings for the Zetec assembly line are stored on aperture cards that can be read using a viewer in the maintenance co-ordinator's office. If a paper copy is needed, it can be printed in one of a number of locations in the factory. Two important issues in the electronic imaging of engineering drawings are the correct choice of display software and the correct choice of display hardware.

5.5.2 Display software

To view drawings on a computer monitor, they must be stored in digital format. If the drawings are currently held on paper or aperture cards, they must therefore be scanned, digitised and stored in one of the many data formats for images. Imaging software is used to view digital drawings. There are many proprietary viewers available including those supplied with tools like Microcosm. The alternative to this approach is to store drawings in their native format and allow a user to access the software used to create the drawings. This ensures that any drawing will be viewed exactly as the draughtsman intended, but it would be expensive to provide enough CAD licences to allow every likely user to access the design software. It would also be both unsafe and unnecessary since read-only access is sufficient for maintenance purposes as long as viewers are provided to support the most popular drawing formats. The Microcosm viewers also allow the user to make hyperlinks to and from objects within the drawing.

5.5.3 Raster or vector ?

Digitised engineering drawings may be viewed as raster scans, or they may be converted to vector format (vectorised) and viewed in that form. CAD drawings are produced and stored in vector format, but they may be converted to raster format if required. A common format for vector drawings is the Autodesk proprietary standard known as DXF (document exchange format). Advantages of vector format are:

1. Legibility - vector drawings have crisp lines, no fingerprints or marks and are usually much 'cleaner' than raster drawings.
2. File size - vector drawings can be stored much more efficiently than raster scans.

3. Editing - vector drawings can be read back into a CAD system and edited with ease. This is a significant advantage for designers, but not if the drawing is to be archived or used in a read-only fashion as in maintenance.

The viewing of raster drawings (even those originally produced using CAD) has become much more popular since the development of the file format known as CCITT Group 4 TIFF. This data format was developed for transmission of facsimiles (faxes) over telephone lines and it features high compression without data loss. Group 4 TIFF is the preferred format for raster images in electronic document management systems, including Ford's corporate document management system.

To convert a paper drawing to vector format, it must be scanned and vectorised, both of which can be done in-house or by a CAD bureau. A CAD bureau scanned the drawings for this project, but it was unclear initially whether the scanned images should then be vectorised or left as TIFF files. The major drawback of vectorisation is the cost. Typical costs at 1998 prices were:

- Scanning an A0 sized engineering drawing to Gp4 TIFF format £10
- Scanning, automatic vectorisation and tidy up to DXF format £60
- Scanning, full vectorisation to editable CAD standards £400

5.5.4 Suitability for Ford hypermedia project

The main advantage of vectorisation in this application is the ease with which Microcosm can generate hyperlinks to objects such as AutoCAD blocks. This functionality is supported in a DXF viewer that is being developed at Southampton University. The viewer is not yet part of the standard Microcosm software, and as such is not supported by Multicosm (the vendor). Nevertheless, the viewer has been successfully used in the Pirelli application and was considered for the Ford application. The DXF viewer supports one of Microcosm's most powerful features, which is the automatic creation of 'generic hyperlinks'. This can save significant authoring effort.

From the point of view of cost, it was clearly preferable to use either an automatically generated DXF drawing or a raster drawing in TIFF format. The version of Microcosm used did not support a TIFF viewer so if Ford's drawings were to be viewed in raster form, they would have had to be converted and stored as bitmap (BMP) images.

5.5.5 Experiments with TIFF and BMP format drawings

A good quality A0 drawing was scanned to produce a TIFF file of 185Kb that was of excellent quality even when viewed at high magnification. When the file was converted to bitmap format the result was a file of 7645Kb that was too large to view with the Microcosm bitmap viewer. When the resolution of the image was reduced, it could be viewed successfully although it was felt that the zoom and pan speed might be unacceptable in the factory environment. As with any other BMP image, Microcosm allowed button links to be made using regions of pixels in the image as anchors. Bitmap was the format adopted for drawings in the Microcosm applications.

5.5.6 Experiments with DXF format drawings

The Microcosm DXF viewer was an experimental piece of software that was developed for the Pirelli application. It was not claimed to be a full implementation of the full DXF standard, only those parts that were required for the Pirelli project (Crowder *et al*, 1996). The DXF viewer was not commercially available but copies were added to Cranfield's copies of Microcosm for the Ford hypermedia project. When tested, the DXF viewer failed to display either a DXF drawing that had been output from AutoCAD or one that had been exported from Visio Technical. However, DXF format images produced by an automatic vectorisation process were viewed perfectly although the images themselves were very poor representations of the original paper drawing.

Following discussions at Bridgend, it was felt that in the team environment, the ability of users to create their own hyperlinks to elements within drawings would be of less value than speed, ease of use and a simple user-interface. It was also felt that there was no advantage in being able to view and create links to drawings in their native format, although this might be very useful in the design office (Malcolm *et al*, 1991).

Table 5-1 shows the results of experiments with drawing file formats.

File Format	Advantages	Disadvantages
Autodesk document exchange format **DXF**	Microcosm DXF viewer can generate automatic hyperlinks using block names as link anchors. Small file size. Proprietary standard that is widely used. Automatic vectorisation software is cheap.	Microcosm's DXF viewer does not implement full DXF standard and failed to read test files except for those produced by automatic vectorisation. High cost of full vectorisation. Poor quality of drawings produced by automatic vectorisation.
CCITT Group 4 tagged image file format **TIFF**	Standard format for document management systems. Lossless compression allows high resolution with small file size. Viewers available with rapid zoom and pan.	No TIFF viewer in the version of Microcosm used. Raster format so not possible to use drawing objects as hyperlink anchors.
Windows bitmap **BMP**	Can use Microcosm BMP viewer. Very common image format Quality considered acceptable for maintenance purposes even if resolution reduced.	Microcosm BMP viewer has slow zoom and pan with large engineering drawings even if resolution reduced. Very large file size at full resolution. Raster format so not possible to use drawing objects as hyperlink anchors

Table 5-1 Comparison between different image formats for drawings

5.5.7 Display hardware

One of the objectives of this project was to empower maintenance teams by giving them direct access to the information they need to do their jobs in a form that is both familiar and easy to use. The form of information that is most familiar at present is the paper drawing which is often taken to the machine under maintenance and used during the job. To replace this operation with a digital drawing which is viewed on a monitor creates problems. Crowder *et al* (1996) found that a portable pen-based computer was acceptable for A4 sized electrical diagrams at Pirelli, but this approach was not felt to be suitable for the A0 sized engineering drawings at Ford. The screen would have been too small to display enough of the drawing at full size, and conventional image viewers cannot easily be zoomed and panned by an operator with a spanner in each hand.

Multicosm is developing a voice-controlled user-interface that allows hands free zooming and panning of large drawings. Data input by voice was attempted later in the project (paragraph 5.17) and there were also experiments with a touch screen (paragraph 5.14).

5.6 Other Media

Although there were several issues to be resolved concerning the ability of Microcosm to display large engineering drawings, it was known that Microcosm could successfully display still video images in BMP format and moving video images in AVI format (Crowder *et al*, 1996). These media are described below:

5.6.1 Pictures

A digital camera was used to collect images of parts of the machine. Many of the photographs in the system were collected by team members since digital cameras are frequently used in the factory to illustrate single point lessons, and as part of Ford's commitment to 'the visual factory'. As well as giving a sense of ownership, the use of photographs collected by users ensured that they were sharing graphical information that was actually of value to the team. Some pictures of proprietary spare parts were scanned using a desktop scanner.

Rendered images of parts of the assembly machine were also used to aid navigation. A 3D-visualisation tool was used to generate the still images and the animated sequences that illustrated machine operation. Since the original machine was not drawn using CAD, the 3D solid models had to be generated 'long hand' by measuring from the drawings or using the co-ordinates that were shown on some drawings.

5.6.2 Moving video and animation

Although Crowder *et al* (1996) used moving video images at Pirelli, this medium was not used in the Ford application. Although animation produces synthetic images that can only imitate the real process, it has several advantages over the use of moving images produced using a camcorder, in terms of clarity of illustration:

- Machine components can be given artificial colours to distinguish them from each other.
- Ancillary equipment such as wiring, ducting and pipes need not be shown.

- Dirt, corrosion and the machine surroundings are not shown.
- Invisible effects such as the heating of the little ends of the connecting rods may be made visible.
- Components or sub-assemblies may be made translucent if required.

5.6.3 Creation of animated sequences

3D Studio Max was used to produce rendered still and moving images of the assembly machine. The timing of the machine motions was entered from the machine manufacturer's timing diagram that illustrates the logic of the automated assembly sequence. The result is that the animations match the timing of each individual motion of the real machine during a full cycle. Since the animations can be run in a continuous manner by looping them, they can illustrate the cyclic processing of several engines by the assembly machine.

5.7 The First Hypermedia Systems

The media collected and the various hypermedia systems that were developed during the project are shown in Figure 5-3. This diagram can be used as a guide to the hypermedia systems, the lessons learned and the reasons for further development work.

The first hypermedia maintenance applications for Ford's Bridgend engine plant were a spare part identification system known as *Microcosm Spares* and a planned maintenance information system known as *Microcosm Belt Change*. The latter contained a description of a planned maintenance task - the replacement of drive belts for the pallet conveyor. The author and a Cranfield researcher - Mr Devendra Fakun - used Microcosm to create both applications. Demonstrations took place at Bridgend where the reactions of staff and team members were recorded. With each demonstration of the system, user feedback was sought and improvements made, where possible.

5.7.1 Microcosm Spares

The first version of this application displayed stores reference numbers as labels which appeared when the user placed the cursor over a region of pixels within a picture of the relevant machine assembly. Following user feedback, the labels were replaced by hyperlinks to a set of 'data sheets' giving details of the spare parts. For proprietary items, these sheets contained information from the vendors' catalogues.

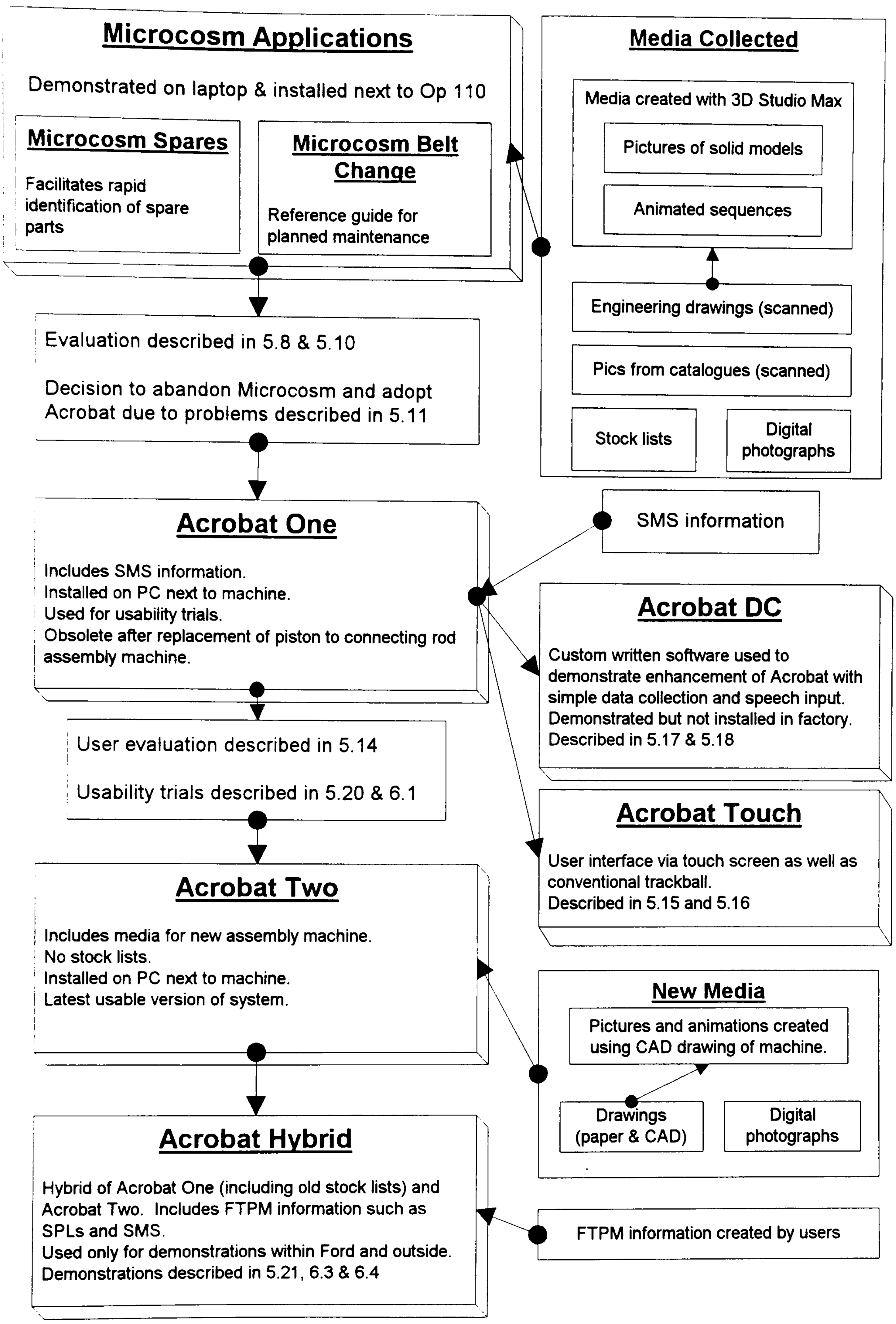


Figure 5-3 Development process for Ford hypermedia applications

5.7.2 Microcosm Belt Change

This small hypermedia application took information from a manual provided by the suppliers of the belt driven conveyor that feeds the assembly machine. There is a scheduled maintenance task to remove old belts that become worn and contaminated with oil. New belts must be cut to the correct length and have the cut ends prepared and bonded together using adhesive and a bonding fixture. The hypermedia version of this manual linked text and illustrations to describe this task. Hyperlinks to a simple spreadsheet allowed the user to calculate the correct length of each belt.

5.8 Evaluation of First Applications

In practice it was found to be impossible to involve all users in the development of the pilot applications since many of them are 'line-tied' and could not easily be released from production. Another problem is that users with little experience of information systems are unable to produce clear specifications (Fischer *et al*, 1996). However each stage of prototype design was tested on those users who were available and enthusiastic, in order to record their reactions and inform the design process. The first applications to be authored using Microcosm were demonstrated to team members using a laptop computer, and comments were invited on each application in turn.

5.8.1 Comments on Microcosm Spares application

Following the demonstration of this application, there were several comments from team members and managers:

- The use of 3D solid models (animated sequences and still images) was felt to be a good way to visualise the machine without stripping it. This was particularly true of some of the more complex mechanisms that are hidden from view by safety guarding or the structure of the machine.
- The ease of use of the hypermedia application (compared to MatLoc) would allow a semi-skilled worker to get hold of spare parts without waiting for a skilled worker. In this way, the technology could be used to empower semi-skilled team members. There remains the problem of the requirement for a signed requisition before parts can be withdrawn from stores.
- The idea of voice control did not seem to be popular with the team members at Bridgend. There was not felt to be any requirement for hands-off viewing of a drawing, and the hands of Ford maintenance workers are usually clean. Team members said they would be too embarrassed to use a wearable computer, or to input commands via a microphone.
- It can often be difficult to find information about proprietary items that do not have individual drawing numbers. The use of hyperlinks to the relevant information would save a lot of time.
- The control of issue of all engineering drawings would always be important. In theory this was possible with the current aperture card system, but in practice it was difficult to achieve. The Bridgend systems manager commented that issue control would be addressed by Ford's new electronic document management system - Image.

- If the systems were made available on the PC belonging to the maintenance co-ordinator (where the aperture cards are currently kept) then access to the systems would be impossible when he was not in the factory. Although team members could always get a drawing from the coders, it was a long walk and nobody is as experienced with the drawing system as the maintenance co-ordinator. The proposed solution was to locate the hypermedia applications on a PC on the shop floor.
- If a particular maintenance problem had occurred before, it would be useful to be able to check for stores reference numbers in the notes that were made by team members when the fault last occurred. It was decided to investigate ways of facilitating team communication through hypermedia.
- The maintenance co-ordinator asked whether users could rotate the solid models in 3D. It was explained that they were only 2D images and that virtual reality technology would be needed to allow users to interact with a 3D image. This was felt to be outside the scope of this project.

5.8.2 Comments on Microcosm Belt Change application

This application was felt to be a good way of familiarising a new starter or an apprentice but it was not felt to be as useful to a skilled or experienced worker. However, experienced team members would find a 'hypermedia memory jogger' containing important data very useful. Such data would include adhesive shelf life and belt lengths for any section of the line. Users did not appreciate the hyperlinks to a spreadsheet used to calculate belt length. This was intended to make the application generic, but users wanted specific belt lengths to be stated for each section of the line. This reaction illustrates the trade-off between ease of authoring, which favours a generic approach and usability, which favours the display of specific information.

5.9 Installation of PC in Factory

The first versions of the Microcosm applications were installed at Bridgend on the PC in the maintenance co-ordinator's office. This allowed him and the team members to evaluate the program in their own time and at their own pace. However, since this office is upstairs overlooking the assembly line and is locked at night, it was necessary to purchase a PC to be installed on the factory floor. A suitable PC was installed in a steel cabinet next to the assembly machine. It was considered important to specify a machine with sufficient graphics capability to allow the user to zoom and pan engineering drawings without suffering excessive delay. The specification of the PC is:

- Pentium 166 with MMX and 32Mb of RAM
- Accelerated graphics card with 2Mb video RAM
- 17" monitor
- 12 speed CD reader
- Trackball pointing device used instead of mouse
- Windows 95 operating system

The PC was not connected to the Ford network, for security reasons and for ease of administration. The Windows policy editor was installed and used to set up user profiles to improve security. This means that all users are required to enter a password but if a user hits the escape key instead of entering a password, the default profile is used. This denies access to 'Windows Explorer' and 'My Computer' to prevent users from moving or deleting files. A password protected administrator profile was set up and this gave full access to all operating system features.

A copy of the hypermedia maintenance application was loaded on the PC and users from each shift were given basic instruction on how to use Microcosm. The nature of the information in the system was also explained. Users were asked to experiment with the system and it was made clear that their feedback would be used to develop it.

5.10 User Evaluation After Installation of Shop Floor Computer

Two months after the installation, a team leader was asked for his views of the applications. He replied that the applications were useful in as much as they gave line workers rapid access to information. However, in his view, they were not as useful as they might be since they did not contain a complete set of information that might be useful to his team. The systems only dealt with spare parts for one machine and only one of the planned maintenance activities on that machine. He would have liked the system to contain a full list of stores numbers for all spare parts and material used in the A1 area.

He also pointed out that IMSs are not currently given access to MatLoc, but that if they were able to source spare parts from the stores there would be many maintenance tasks that they could and would carry out. An example of one such task is changing of the Statec (pallet transponder) reader blocks. He suggested that rather than navigating to a spare part via hyperlinks, a simple lookup function would enable searching for many simple items not related to a particular machine. Examples are rubber gloves, knife blades, cleaning materials etc.

5.10.1 Comments from other team members

One team member commented that although the use of graphical media might help new starters to become familiar with the machine, all his colleagues were already familiar with it and what they really needed was rapid access to part numbers only. Many team members knew that the application did not contain a complete set of stores reference numbers, so they did not use the system as much as they would otherwise have done.

The maintenance co-ordinator commented that he would like brass tag numbers for all parts shown on application. Assets such as items of manufacturing plant are all given such a number, and there is one for the piston to connecting rod assembly machine.

5.10.2 Problems with PC

A recurring problem during the development of the hypermedia application was the crashing of the PC. The cause of this is not known, but it never happened whilst the researcher worked on the system or during demonstrations. It may have been caused by power surges in the factory mains supply or by users accidentally switching off the computer or tampering with the operating system. The evidence of a crash was that the monitor had been turned off and the computer needed to be re-booted, which required a security password.

Attempted solutions were the use of system policies and user profiles as well as removal of shortcuts to applications such as Microsoft Paint. In a discussion with a Ford systems manager at Bridgend, it was revealed that 'hacking' of PCs was a real problem especially on the night shift. Ford systems managers did not support the PC used for the development hypermedia application. When it crashed it remained down until the next visit by the researcher.

5.10.3 Problems with window size and location

An early problem with the Microcosm application was that the system did not close down a window when it opened a new one. Eventually the Windows desktop became filled with windows and was confusing for users. Microcosm allows authors to control the size of windows and this was attempted, but in the opinion of many users the result was even more confusing. The Microcosm developers are designing a means of simplifying window size and location for users who do not want or need the flexibility provided by the original system.

5.10.4 Lack of use of the system

Although the system was often unavailable for the reasons given above, even when it was available it was not used as often as had been hoped. Several explanations were offered for this but the most common ones were:

- The information contained within the pilot system related only to Operation 110 so that the system was not a comprehensive resource for the teams who were responsible for the A1 area. If such a system does not contain all the information likely to be required, users may be likely to look elsewhere if they are in a hurry.
- The Zetec assembly line had been operating for several years, during which time maintenance workers had developed informal sources of information such as private notebooks, sketches and annotated drawings. Team members felt that they understood the machine well and that the hypermedia system did not add much to their understanding.
- Users accepted that the hypermedia system could be a rapid source of the information required to solve a problem that had not occurred before. However, they had to feel inclined to use the system in order to discover this for themselves.
- The piston to connecting rod assembly machine is actually very reliable so team members were not inclined to use the hypermedia system out of necessity. The users who had most experience of the system tended to be those who had most interest in it and therefore used it out of curiosity.
- The complexity of the Microcosm user-interface undoubtedly contributed to lack of system use. Team members who had a technical interest in hypermedia (usually those with home computers) were interested in the application. However Microcosm offered powerful features for which most team members found no use and its poor imaging of engineering drawings was frustrating for most users.

5.11 Problems with Microcosm

Microcosm is a powerful hypermedia tool with many innovative features such as the concepts of separate 'linkbases' and 'generic links'. However these features were actually found to be of limited value in the development of the Ford pilot system. There were also several bugs and more serious problems that emerged during the project. The most serious problems that were experienced are described below.

5.11.1 Viewing engineering drawings

The limitations of Microcosm for viewing large drawings have been described above. Although the Microcosm bitmap viewer was used to display engineering drawings, this viewer proved to be too slow and unwieldy for factory users. Unfortunately the ability to view engineering drawings and follow hyperlinks from drawn features was an essential feature of the application and a determining factor in the success or failure of the project. The current version of Microcosm is now said to be able to handle TIFF images.

The difficulty experienced by users when trying to zoom or pan a drawing was felt to impose an extra and unnecessary cognitive load on the user. Microcosm did not use features such as a different cursor icon to indicate background processing to the user. One result of this is that the slow viewer caused users to feel they had 'broken' the system, or to walk away in frustration. Some users who were frustrated by the slow viewer would use the keyboard or trackball to enter commands during processing which slowed image loading even further.

5.11.2 The power of Microcosm

The power of the Microcosm hypermedia environment is one of its unique features. To allow users to make use of this power, they must be presented with a more complex user-interface than that used by simpler tools. The Microcosm user-interface was found to present problems for workers in the Bridgend engine plant. Here, a simple and intuitive user-interface was felt to be far more important than the ability of users to define their own hyperlinks. Workers in production/maintenance teams at Bridgend were generally found to be inexperienced computer users who expected to use a hypermedia information system infrequently, and for reference only. They did not value the power of an open hypermedia system. It was accepted that at present, the authoring effort and maintenance overhead caused by the need to provide 'hard' hyperlinks may be the inevitable cost of preparing a user friendly application that is suitable for a factory environment.

5.11.3 The lack of portability of Microcosm applications

The most serious problem experienced by the hypermedia system authors was the lack of portability of Microcosm applications. In order for Microcosm to function correctly, several files are needed at different locations on the hard disk. Great care had to be taken when transferring these files from the computer used to author the application to the one used in the factory to access the media. Care was necessary to ensure that file and directory names were duplicated accurately between computers and that the linkbases could access each document in the docuverse correctly. The file transfer process was found to be far from straightforward and always caused problems. The transfer of an application could not easily be attempted by anybody except the authors, and experienced Microcosm users could not be relied upon to resolve any problems experienced. The vendors offered assistance with the creation of Microcosm application which could self install from a CD. This assistance was in the form of consultancy, which suggests that the process was indeed quite complex. According to the vendors, the portability problems have been cured in later versions of Microcosm.

5.11.4 Navigation

In the Microcosm environment, the user navigates between different media using a combination of different types of hyperlinks and a graphical 'Select a Document' dialog box that works like Windows Explorer. This gives the user great freedom to navigate through a large docuverse. For example, a 'one to many' text link may be created that would allow a user to select one of a number of possible destinations from a particular node. However such freedom requires the use of the 'Select a Document' dialog box as a navigation aid to ensure that the user does not become lost in the application. This was found to be unpopular in the factory and a solution was the creation of special navigation screens. These screens used simple button links (hard coded, one-to-one links) to take the user to particular locations and a back button to return to the navigation screen. The Microcosm vendors discourage such a heavy use of button links and it is undoubtedly what the designers of Microcosm were trying to avoid. However, the use of such crude links was felt to be necessary to satisfy the navigation requirements of the factory.

A 'back' button is a great comfort to an inexperienced user who might get 'lost' in the hypermedia, but since there is none provided in Microcosm, wherever a back button is required it must be inserted manually. The vendors offered to help create features to assist users in navigation, but it was felt that if possible a standard hypermedia authoring tool should be used rather than a bespoke piece of software.

5.11.5 Authors and users

Microcosm does not provide separate environments for users and developers. This effectively means that the user can modify the hypermedia application, although of course the media in the docuverse can be protected through the Windows operating system. Another consequence of this is that neither the Microcosm tool bar nor the menu bar can be tailored to restrict user actions without special programming.

5.11.6 Difficulties with linkbase editor

The Bridgend hypermedia applications make use of graphics such as drawings, pictures, tables and photographs for communication rather than pure text. The Microcosm linkbase editor is more difficult to use with graphics than text. Although it is easy enough to <u>create</u> button links in graphical media, difficulties were experienced when locating these links for editing or deletion. Nearly all the hyperlinks in the Bridgend applications are graphical button links, which made maintenance of the applications more time consuming than necessary due to the shortcomings of the linkbase editor.

5.12 Change of Hypermedia Authoring Tool

The limitations of Microcosm led to the decision to use a different authoring tool. As well as the features identified by Wilson (1996), experience with Microcosm and discussions with shop floor users indicated the following additional features which would be desirable in a hypermedia information system:

- Clear presentation of large (i.e. A0) engineering drawings
- Ability to zoom and pan around images in a rapid and intuitive manner.
- Highly intuitive user-interface for minimal (ideally zero) user training requirement.
- Flexibility to design aids for navigation around the media that are very clear, to avoid user feelings of 'lostness'.
- Low cost, which was felt to be important if the concepts developed were to be relevant to smaller manufacturers.

As well as a search through vendor literature, evaluation copies of five popular hypermedia tools were tested against the above criteria. Systems tested were Macromedia Authorware, Macromedia Director, Asymetrix Toolbook, Aimtech IconAuthor and Adobe Acrobat Exchange.

5.12.1 Adoption of Adobe Acrobat Exchange

Acrobat Exchange was the only software that fulfilled the requirement for imaging engineering drawings. To do this, the drawings must be converted to Adobe's portable document format (PDF). Again, the resolution of large images must be reduced to allow Acrobat to zoom and pan the image with adequate speed. The results however were far superior to the Microcosm bitmap viewer. Acrobat does not offer the same flexibility as Microcosm to present detailed and complex information according to user and task (Wilson, 1996) but it does offer several other features which were recognised as highly desirable such as:

- Portability. Copying an application from the authoring computer to the user's PC is a trivial exercise as long as filenames and locations are maintained.
- Documents in PDF format can be viewed with Acrobat Reader, which is freeware.
- Plug-in software can be written by a third party to enhance the basic Acrobat Exchange and/or Reader software. Popular and robust plug-ins such as the text-based search tool and the forms tool are supported by Adobe.

Perhaps the most important feature of Adobe Acrobat is its ubiquity. Although it is proprietary software its data structures are published openly which allows plug-ins to be written. This has led to the adoption of PDF as a data standard. A standards based approach is particularly important when creating a hypermedia application like the Ford system, which uses media that was supplied in a wide range of different data formats. The hypermedia features of Acrobat also gave the flexibility to test many different approaches to the design of a user-interface. The way in which the problems experienced with Microcosm are addressed in Adobe Acrobat Exchange are shown in Table 5-2 which also shows how both Microcosm and Acrobat adhere to data standards and how they relate to the world-wide web.

	Microcosm	Acrobat
Suitability for imaging engineering drawings	Slow bitmap viewer and DXF viewer is experimental. Zooming and panning is difficult. No TIFF viewer in the version of Microcosm used.	PDF can be created from any drawing format. Zoom and pan is acceptable in terms of speed and ease of use. Not as good as viewers in document management systems.
Hyperlinks	Very powerful hyperlinking features which makes authoring and maintenance of large applications less time consuming and gives users great flexibility. Button links discouraged. Users can create links.	Simple 'hard links' which must be created by authors and cannot be edited by users with the reader only. Acceptable for factory users since much better than paper alternative, very robust and intuitive. May cause a high maintenance overhead in large systems.
Portability	Big problem in the version of Microcosm used during the project. Portability problems now said to have been cured.	Very simple and robust. Application can run off a CD-ROM if the CD reader is fast enough. This makes demonstrations less risky.
Navigation	'Select a Document' dialog is not easy for inexperienced user. No back button. Can design graphical aids to navigation if required but button links are discouraged in favour of more powerful types that can be made by user.	Users navigate using a combination of Acrobat toolbar and button links that can be assigned one of a range of navigation functions. Authors have complete freedom to design graphical aids to navigation. Programmers can write plug-ins to assist.
User environment	Little distinction between authors and users even with password protection. Source documents can be protected from editing but linkbases cannot, unless password protected.	Reader environment is very similar to but less powerful than Exchange. No editing possible through Acrobat Reader. Even if users have a copy of Exchange, they cannot edit a document that has been password protected.
Authoring	Authors need training. Not difficult but care is needed. May need programming skills to enhance functions of Microcosm.	Very easy. No training is needed. Good on-line guide with examples. May need programming skills to write plug-ins.
Maintenance	Linkbase editor is very difficult to use and seems to be aimed at text based links, which can be found more easily.	Exchange allows easy access to hard links to different types of media (e.g. sound, movies, forms, applications)
Web	Use product related to Microcosm called WebCosm.	Acrobat Reader will plug into popular browsers. However browsers slow down the imaging of drawings.
Adherence to standards	Makes links to documents in native formats through the use of a set of viewers. Viewers available for common standards such as BMP, RTF, XLS and AVI. No TIFF viewer on version used.	Must convert every document to PDF (except AVI movies that are embedded in documents and played using Microsoft media player). Not a problem since PDF is a very common publishing standard and is now accepted by CALS community.

Table 5-2 Comparison between Microcosm and Acrobat

5.13 Description of Acrobat One Application

The first hypermedia application that was authored using Acrobat is known as *Acrobat One* and uses the same media as the Microcosm applications. However, the presentation of the media was different in terms of its structure and navigation.

5.13.1 Structure of the Acrobat One system

The principle behind the structure of the application was that the user should be able to 'drill down' to information about the smaller components starting at the level of the assembly machine itself. It was known that some workers preferred to use engineering drawings to identify parts while others preferred to look at the machine itself. Others might know the name of the relevant part and wish to locate it by this name. Three methods of navigation were therefore supported. All used button links (i.e. links defined by the authors) to navigate from a higher level to a lower. Whether users chose to follow drawings, pictures or text, they would see three levels of information. This information related to:

1. The main assembly of the machine.
2. The major sub-assemblies of the machine.
3. Individual components and devices (supplied by vendors or the machine builder).

The structure of the application and the relationship between the media are shown in Figure 5-4. This structure can accommodate the maintenance information of a much bigger machine as well as other types of information such as planned maintenance task descriptions. An example of such information was added later. The structure is an example of a simple hypermedia web where users can follow one of a number of paths between different pieces of information. This has the advantage of flexibility, allowing the same set of information to be presented to a number of different users in a sequence decided by them. One well-known disadvantage of the web approach is the ease with which users can become 'lost'. This has been avoided in this application through the use of coloured tabs that are always visible.

5.13.2 Tabs for navigation

The horizontal and vertical tabs belonging to one of the sub-assembly level pages are shown in Figure 5-5. The tabs are actually link anchors. When users click on a tab, they are returned to a familiar screen such as the main engineering drawing. There are three vertical tabs each of which returns the user to one of the three machine level media. There are also several horizontal tabs that take the user between the sub-assembly drawing, the picture page (3D model, photo and animation) and the part lists. Each component for which there is a component level page is represented by a coloured link on the appropriate part reference. The colours on the link show whether the part is a made or bought item.

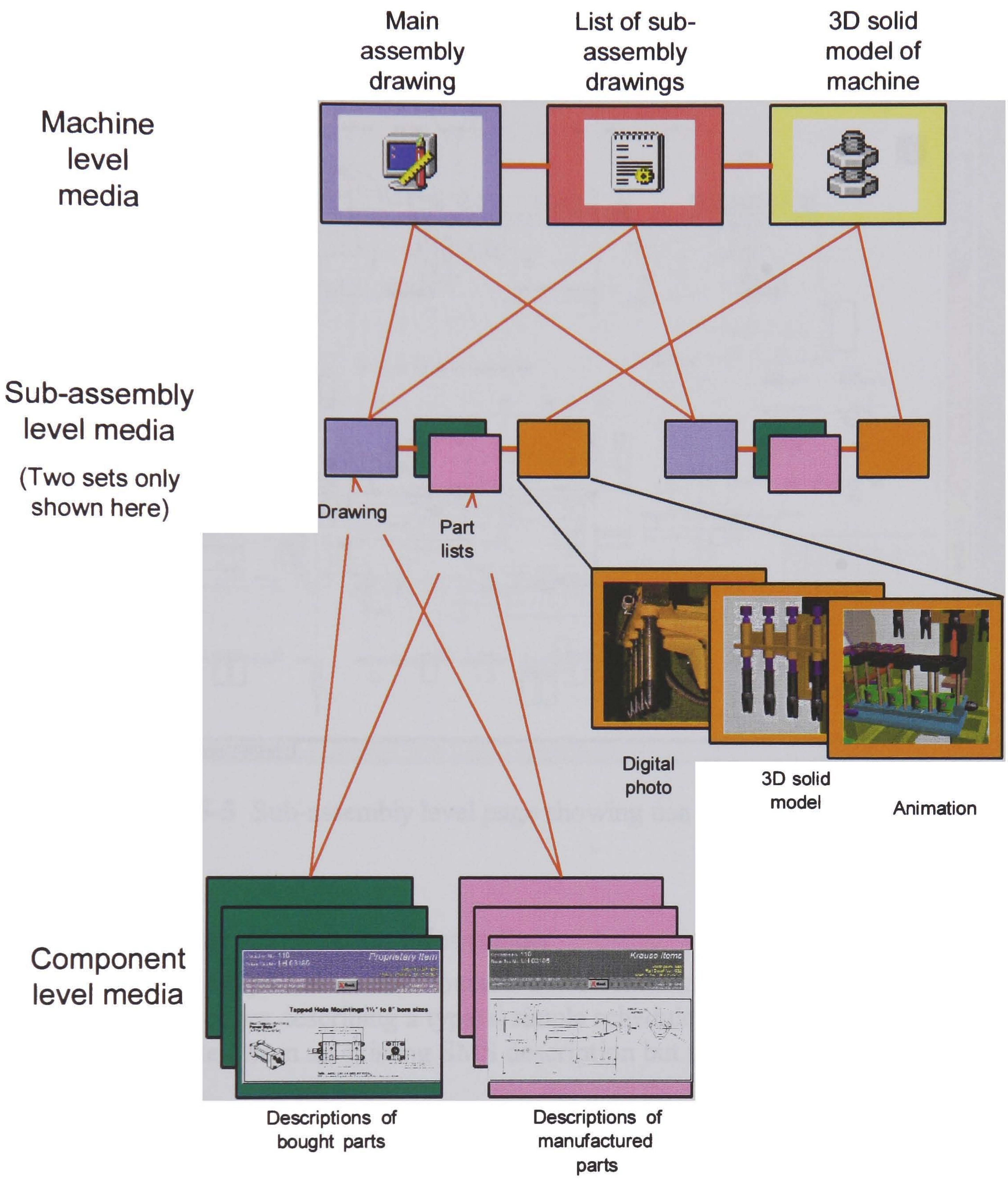


Figure 5-4 Structure of media in Ford maintenance system

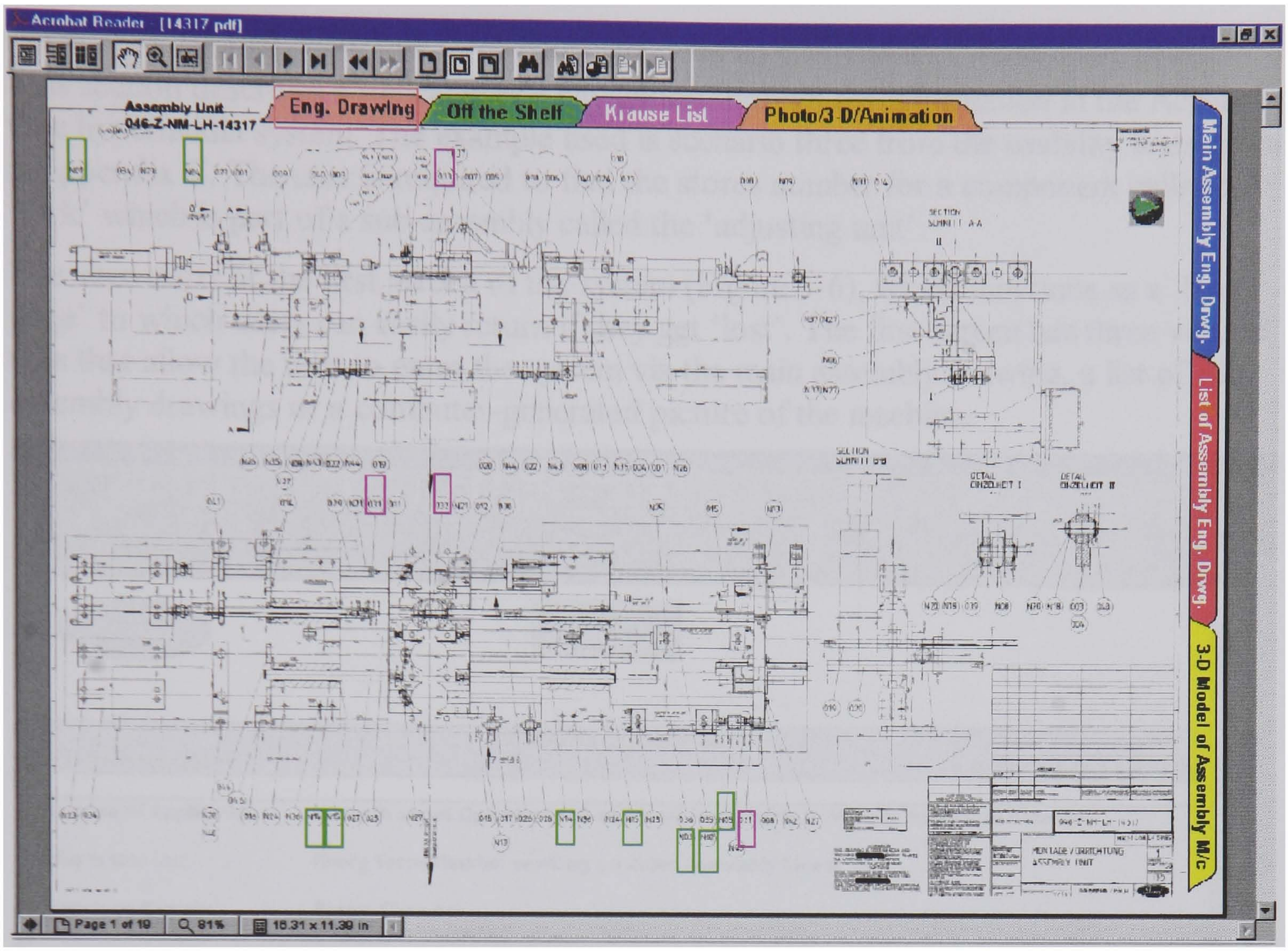


Figure 5-5 Sub-assembly level page showing use of coloured tabs

5.13.3 Scheduled maintenance information

One of the sub-assembly level screens contains a horizontal tab marked **SMS Tasks** that is linked to a set of pages describing a typical simple scheduled maintenance activity. The information was taken from an existing SMS description but the text was enhanced with digital photographs.

5.13.4 Text search

Version 3.0 of Acrobat Exchange allows authors to create indexes which users can search with the Acrobat Reader. This is a very powerful feature that is both easy to use and can significantly speed up the identification of spare part information. Users may either use the hyperlinks to drill down to the information they require, or simply type a keyword that is used to search the index for matches in the entire application. If an engineering drawing is converted from a vector format such as CGM, then the text in the drawing is preserved. It will be included in any indexes that are created, which allows a text search to include parts of the engineering drawing.

5.14 Use of the Acrobat One System

This section describes a typical user's navigation through the information in the Acrobat One hypermedia system. The example used is scenario three from the usability tests given in appendix C. The user is required to find the stores number for a component called a 'fork' which is part of a sub-assembly called the 'adjusting unit'.

The user starts at the first screen of the system (Figure 5-6), which functions as a 'home page' to which users can easily return if they get 'lost'. The first screen has three vertical tabs that allow the user to enter the system via the main assembly drawing, a list of sub-assembly drawings or a computer-generated picture of the machine.

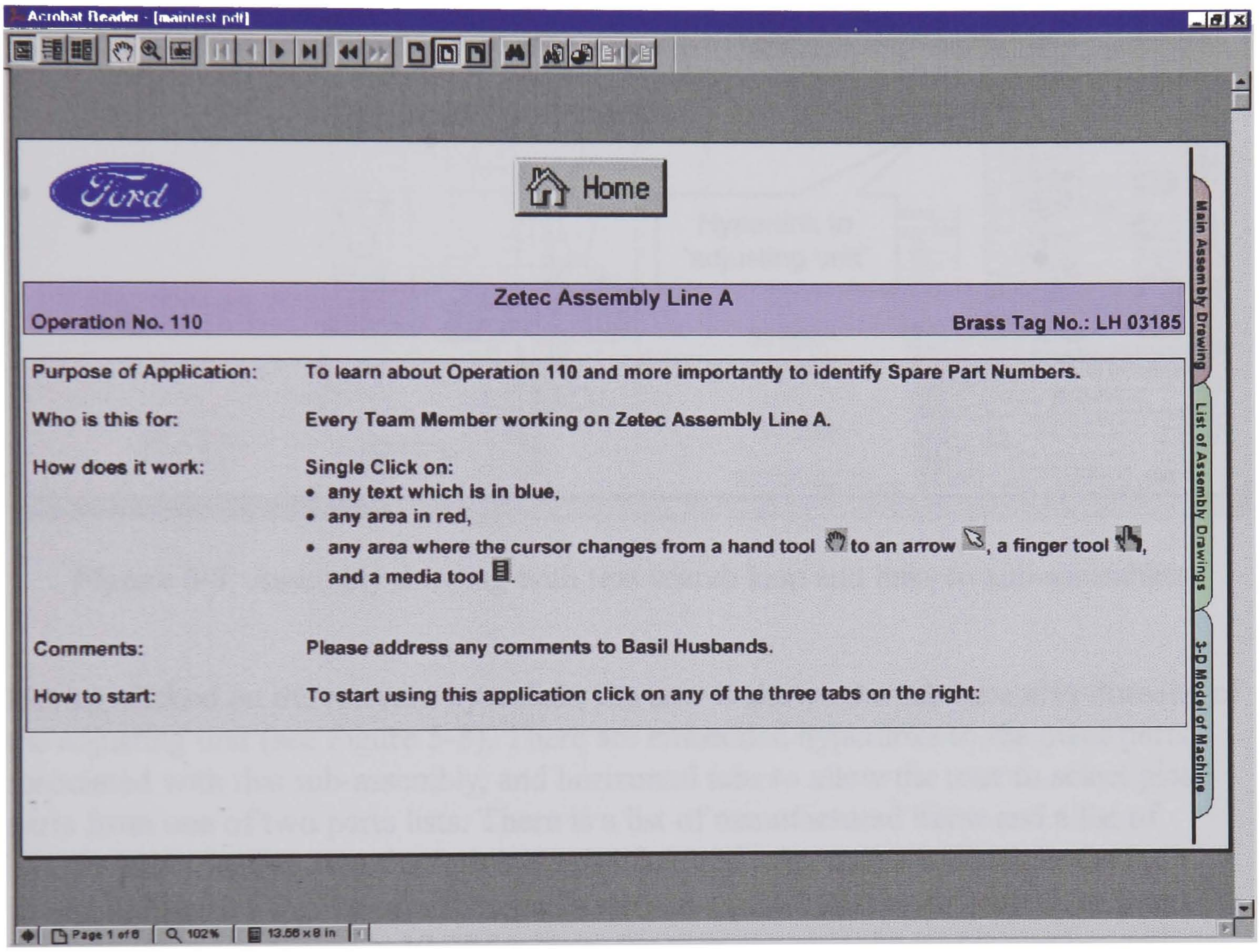


Figure 5-6 First screen showing vertical tabs

Although the fastest route to the desired information is usually to execute a text search, new users may feel more confident if they use the hyperlinks. It will be assumed that the user has chosen to enter the system via the assembly drawing and to follow the hyperlinks. The text search icon and the hyperlink to the 'adjusting unit' are shown in Figure 5-7.

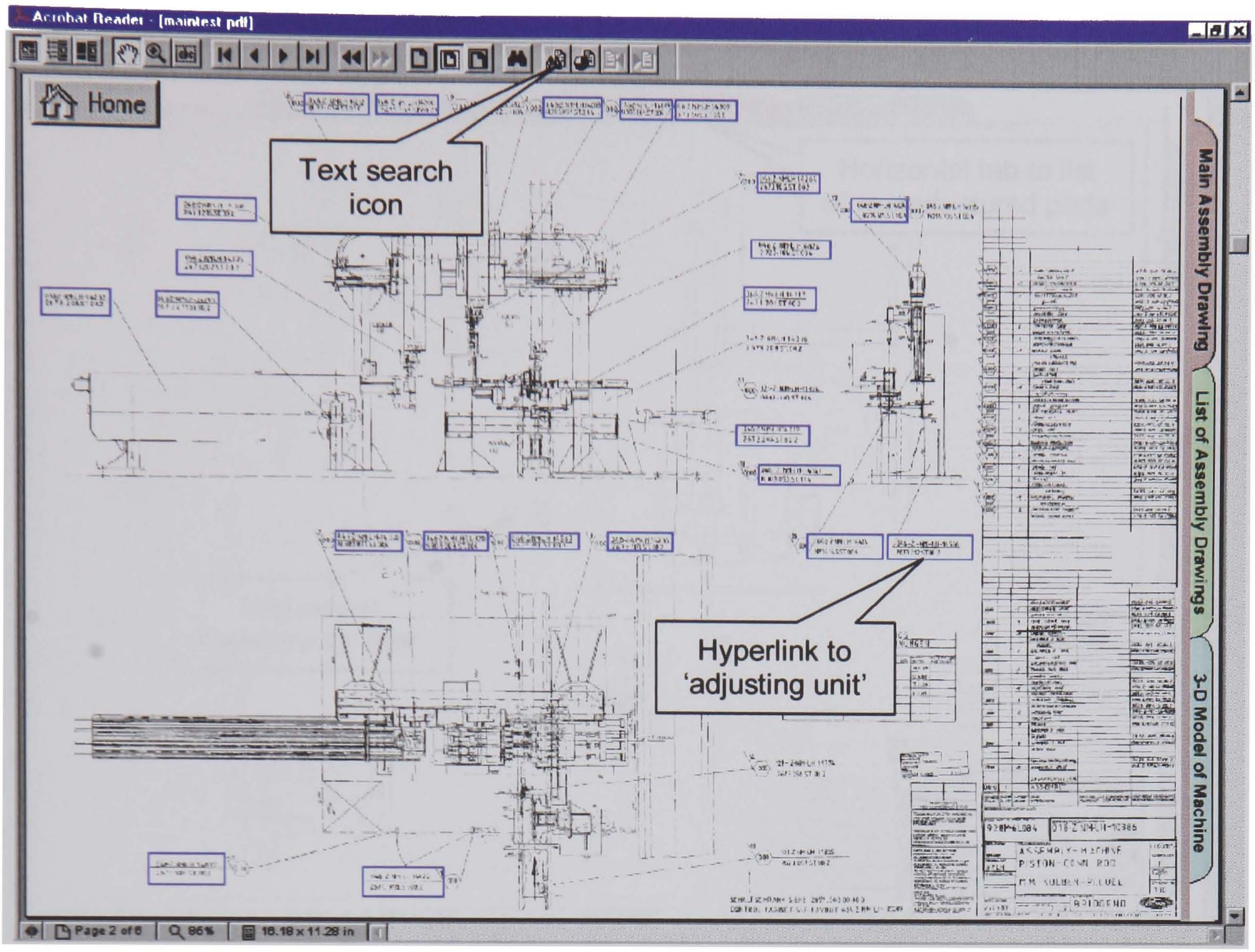


Figure 5-7 Assembly drawing with text search icon and links to sub-assemblies

Having clicked on the relevant hyperlink, the user is shown the sub-assembly drawing of the adjusting unit (see Figure 5-8). There are embedded hyperlinks to the piece parts associated with this sub-assembly, and horizontal tabs to allow the user to select piece parts from one of two parts lists. There is a list of manufactured items and a list of bought items. In this case the fork is a manufactured item, and it is found in the list shown in Figure 5-9. The user then picks the piece part from this list, which presents the drawing shown in Figure 5-10. From here, the user can read the stores number and examine the drawing using the zoom and pan functions of Acrobat. If a printer is connected, the drawing can be printed.

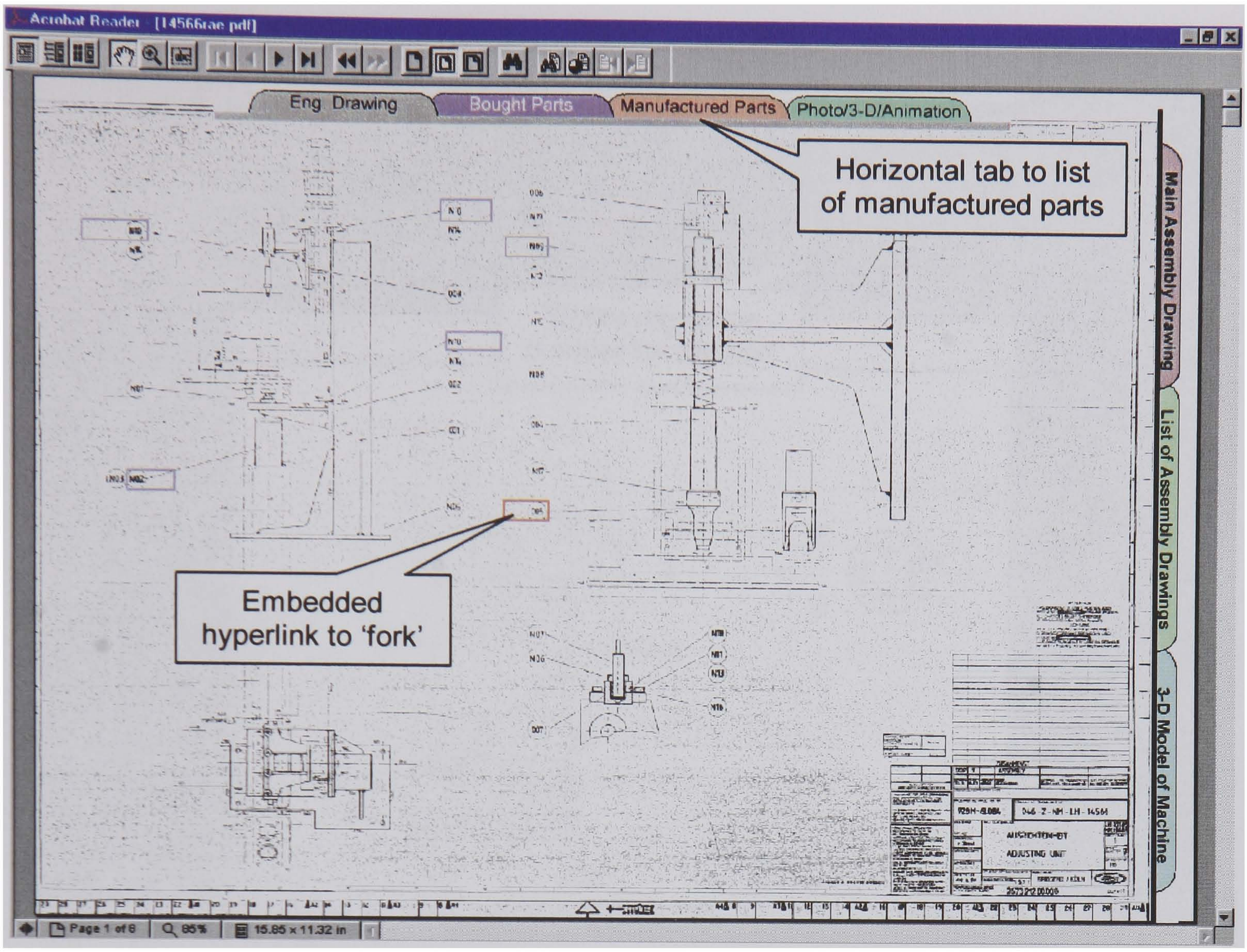
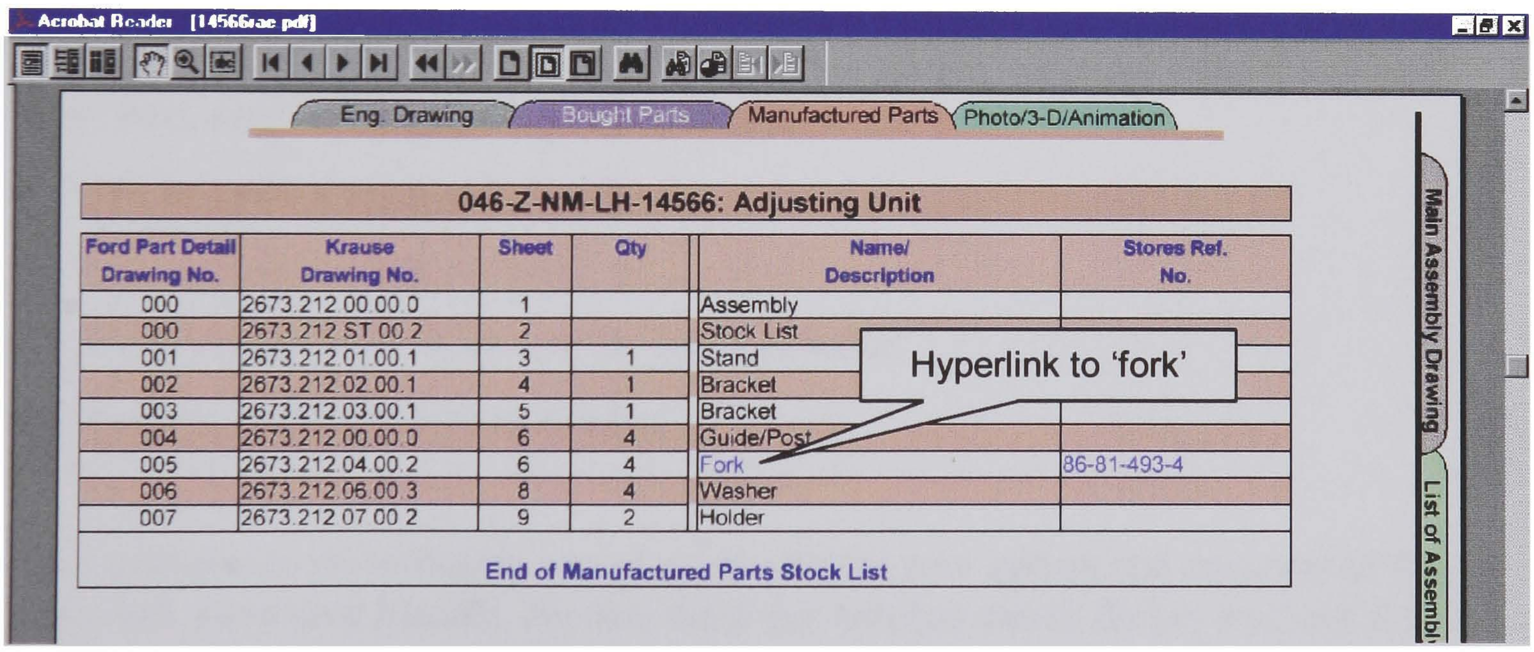


Figure 5-8 Sub-assembly drawing showing links to piece parts and horizontal tabs



046-Z-NM-LH-14566: Adjusting Unit

Ford Part Detail Drawing No.	Krause Drawing No.	Sheet	Qty	Name/ Description	Stores Ref. No.
000	2673.212.00.00.0	1		Assembly	
000	2673.212.ST.00.2	2		Stock List	
001	2673.212.01.00.1	3	1	Stand	
002	2673.212.02.00.1	4	1	Bracket	
003	2673.212.03.00.1	5	1	Bracket	
004	2673.212.00.00.0	6	4	Guide/Post	
005	2673.212.04.00.2	6	4	Fork	86-81-493-4
006	2673.212.06.00.3	8	4	Washer	
007	2673.212.07.00.2	9	2	Holder	

End of Manufactured Parts Stock List

Figure 5-9 List of manufactured piece parts associated with the adjusting unit

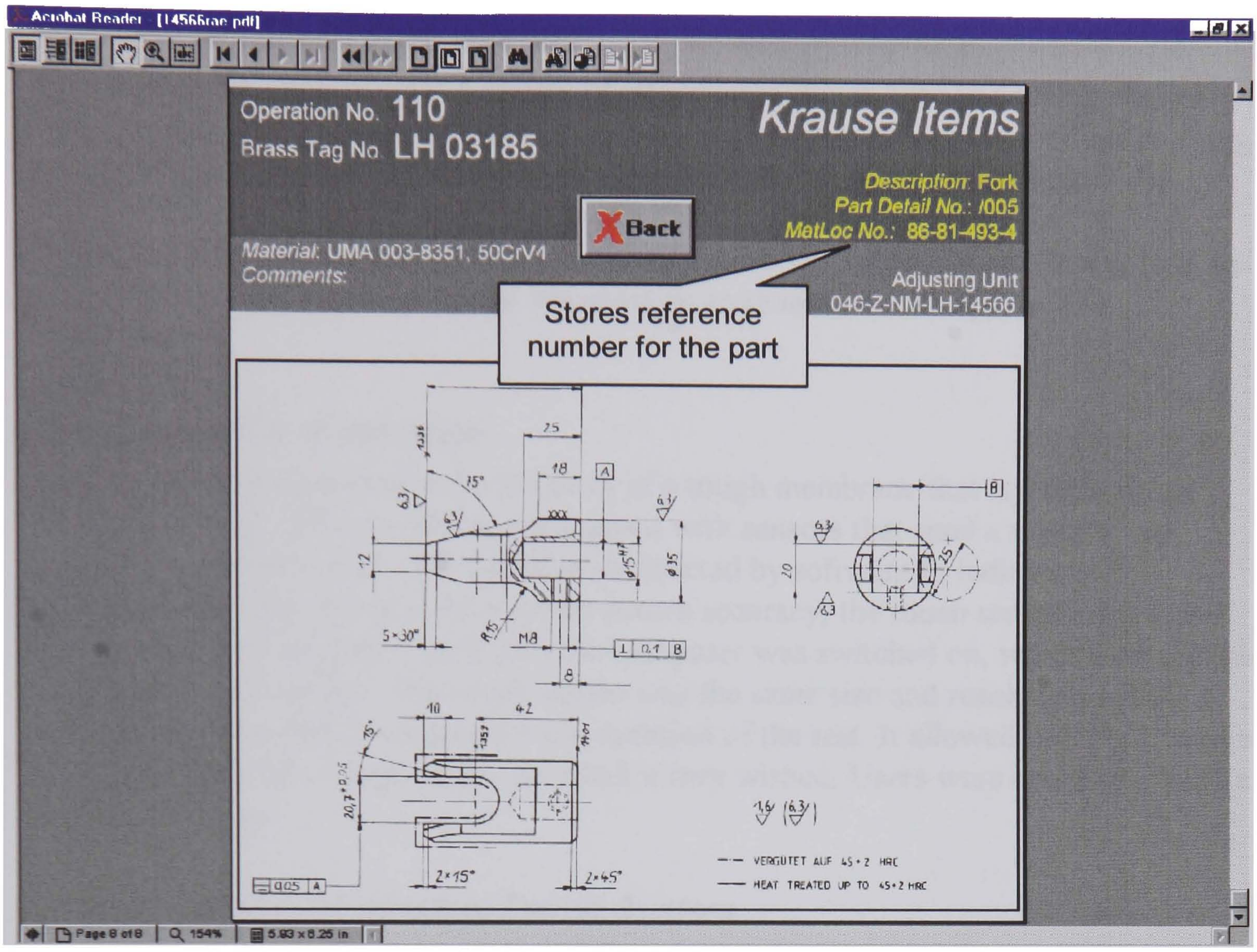


Figure 5-10 Piece part drawing of the fork showing stores reference number

5.15 User Evaluation of Acrobat One System

After the first demonstrations of the Acrobat One system, reactions from the factory users were very favourable. Typical comments were:

- "This is much more professional"
- "Easy to find our way around"
- "The drawings load faster and the zoom is better"
- "You get to the bit you want faster"

The maintenance co-ordinator was pleased with the new system and commented that it was much more user friendly. He also liked the Acrobat search facility and said that it would be very useful in his office. This was before he was given access to Ford's new 'Image' system, which also has a powerful and user-friendly search facility.

One team leader commented that he felt that engineering drawings are actually not very useful on the shop floor. He felt that a more appropriate graphical tool might be a 3D model that allowed a user to peel off layers of the machine to access information about components and assemblies that are not visible from outside the machine. He felt that such a feature would appeal to more team members.

5.16 The Acrobat Touch System

The hypermedia application is a source of information that is used in a read-only fashion. There is little need to enter information into the system via the keyboard unless carrying out a text search, and users interact with the computer mainly via the trackball. In principle therefore, there is no reason why a touch screen might not be used instead of the trackball. It was decided to evaluate the use of a touch screen in the factory, and an example was hired for the purpose. No changes were made to the hypermedia application.

5.16.1 Principle of operation

Most modern touch screens take the form of a tough membrane that is attached to a standard monitor. The membrane is equipped with sensors that send a signal to the computer via a serial port. The signal is interpreted by software to indicate user interaction with the monitor. In order to ensure accuracy, the touch screen used in this project required calibration each time the computer was switched on, which was a simple but necessary procedure. The touch screen was the same size and resolution as the standard monitor that it replaced for the duration of the test. It allowed users to continue to interact with the system via the trackball if they wished. Users were asked to evaluate the touch screen.

5.17 Evaluation of Acrobat Touch System

The operation of the touch screen in the factory was unsuccessful. On several occasions when visiting the factory, it was found that the monitor had been switched off because the touch screen had stopped working properly. It was not possible to trace the cause of the failures and when the researcher had made sure the touch screen was working properly, users were asked to comment on its usability.

If the operating system had been more robust, the touch screen might have been available more often, however it was felt that it would still have been of limited use. Although it did allow rapid access to information via button links embedded in the graphics, it was very difficult to use the touch screen with the Acrobat toolbar. This was because the icons on the standard Acrobat toolbar are too small to allow reliable execution of the desired commands, especially when compounded by parallax effects that affected control of the cursor. The idea of using a touch screen was therefore abandoned although a touch screen might still be a suitable way to interact with an Acrobat hypermedia application if the standard icons were replaced by fewer, bigger icons. This might be achieved by writing a plug-in.

5.18 Development of Data Collection System

As a read-only system, the Acrobat One hypermedia information system does not allow collection of breakdown data. This is one of the central features of a conventional CMMS, and the absence of such a feature is a drawback of the Acrobat One application. It was decided to try to add the functions of a simple CMMS, but to do so in a way that was as user-friendly as possible. Chapter 2 has described the inadequacy of conventional CMMS software in a teamworking environment. Experience at Bridgend and elsewhere (Wynne and Starr, 1998) suggest that one of the main reasons for this is the problem of getting factory workers to record accurate fault description information. Paper forms, bubble cards or a computer terminal are common methods of collecting both structured and free form data.

5.18.1 Structured data

Structured data is collected by asking users to make selections from a list of possible choices. On a paper form, this might be achieved by asking users to tick boxes to indicate which asset has failed as well as fault type, duration, severity etc. The bubble card method is an automated version of this approach. If data is to be collected using a computer with a graphical user-interface (GUI), common approaches are menus, radio buttons or check boxes. The main drawback of such methods is that they rely on the provision of a suitable list of choices for user selection. Such a list must be comprehensive enough to cover all major failure modes, but concise enough to be usable by people under time pressure. As with questionnaires, the design of data collection forms is a skilled activity. Because of the difficulty of accurately specifying all likely choices for data entry as well as a suitable definition of 'miscellaneous', most data collection methods allow users to enter free form data as well as structured data.

5.18.2 Free form data

This is usually entered as text, where the size of a box or the number of lines or characters may be used to indicate the maximum length. Although this method of data collection allows a more precise description of a fault in the user's own words, it creates data analysis problems. The accurate classification of free form data into defined categories requires a degree of expertise and is a time consuming clerical task. A further problem is that users may be unwilling to provide a detailed description if they are short of time. If data is collected via a computer, many factory workers are very reluctant to use a keyboard to type detailed fault descriptions.

One method of collecting free form data is to record speech. Commercial speech input software for use with word processors requires a degree of 'training' before the software can reliably recognise a user's speech patterns and convert them to text. This is a disadvantage in a teamworking environment since it is unlikely that time would be made available to train the software to recognise the voice patterns of all likely users. However, it was felt that merely recording the spoken fault description information would be a useful feature, so it was decided to experiment with speech input as a component of the Ford hypermedia information system. Audio compression and the availability of cheap magnetic media have made storage of large volumes of recorded speech feasible. Once recorded, spoken descriptions of breakdowns could be reviewed off-line, with relevant information being transcribed by an audio typist if required. This work is not central to the thesis, and is described here only briefly. Pollard (1998) provides a fuller description of the work.

5.18.3 Data collection with Acrobat forms

To address the main shortcoming of the Acrobat hypermedia application, it was decided to experiment with the use of Acrobat forms for collecting structured breakdown data. This would be augmented by speech entry for unstructured data.

The use of the Acrobat forms plug-in requires that Acrobat documents be resident on a web server and viewed through a web browser. The data that is collected via the form is submitted to the web server using a program called a CGI script. Users' speech was recorded using a special purpose program that was executed from the Acrobat form. Problems were experienced with the use of Acrobat forms in this application and it was decided to collect both structured and free form data using a program written in Microsoft Visual Basic. The result was the *Acrobat DC* system.

5.18.4 The Acrobat DC system

In this application, the data collection program behaved as a master application that allowed the display of hypermedia documents by calling Acrobat Reader as a slave application. Structured data was collected and stored in a database in a conventional manner, with free form data being recorded as speech. Again, there was no attempt to use speech recognition, but users were given the chance to review their spoken fault descriptions before saving them to the database. It was this application that was demonstrated to managers at Bridgend.

5.19 Evaluation of Acrobat DC System

A full description of the development of the Acrobat DC system is given by Pollard (1998), and what follows is a summary of the results. The Acrobat DC system was demonstrated to Ford managers who felt that this approach to the collection of reliability and maintainability (R&M) data was very promising. Although the feasibility of fault logging by voice was demonstrated, the Acrobat DC system was not considered robust enough for the shop floor at this stage.

The provision of a secure and robust system was one of the aims of the project. This was to be achieved through the development of a 'browser shell' which disabled many of the operating system functions so that users could only access the fault database and read the hypermedia information through the Acrobat Reader. Although this approach was secure, an unfortunate side effect was that the browser slowed down the Acrobat Reader significantly. The browser software also caused some of the Acrobat hyperlinks to behave inconsistently. If a PDF document that had already been opened was accessed again via a hyperlink, then the user would be taken to the last page that was read, whether this was the correct link destination or not.

When the Acrobat DC system was presented to shop floor users, although the ease of fault logging was appreciated, some felt that the need to wear a microphone or speak into one would embarrass many workers. Some areas of the factory were also felt to be too noisy for reliable voice input. The main reason that these developments were not pursued further at Ford was the introduction of TEM, the global maintenance management system. This has a fault logging interface which was felt by Ford systems managers to be usable without enhancement, although the inclusion of voice input might be considered in the future.

5.20 New Assembly Machine and Acrobat Two System

During the Christmas 1997/98 shut down period, the piston to connecting rod assembly machine was replaced by a newer more flexible machine that could assemble parts for new engine variants. Whilst the new machine shared some components and systems with the old one, it was a different design in most significant respects including the logic and timing of its motions. The installation of the new machine rendered most of the hypermedia maintenance information system obsolete, so the application was rewritten with new media to become the *Acrobat Two* system. This provided a strict test of the ease with which the Acrobat application could be updated. The update included the following activities:

- Scanning of new drawings.
- Photography of new machine assemblies.
- Generation of 3D models of new machine assemblies although some old models were reused or modified.
- Definition of machine motions and timing
- Rendering of animated sequences
- Conversion of media to PDF
- Improved design of pages for hypermedia application
- Addition of hyperlinks between nodes of new application

A list of spare parts for the new machine was not available at the time of writing so the new hypermedia application is incomplete. For this reason, it was decided to carry out usability trials using the Acrobat One system.

5.20.1 Use of CAD for new assembly machine

The new machine was represented by a new set of engineering drawings. These were only available on paper, which meant they had to be scanned before they could be used in the hypermedia application. The main assembly drawing had been produced using CAD and the machine builders were able to supply this drawing in DXF format. The drawing was read into AutoCAD to produce a PDF version of the drawing directly, without scanning. The AutoCAD assembly drawing was also used to construct the 3D solid models of the new machine, which significantly reduced the time needed to generate the models and the animated sequences. It would have been faster still if the machine builder had used 3D solid modelling as part of their design process - a practice that is expected to become more common.

5.21 Usability Trials With the Acrobat One System

The purpose of these trials was to evaluate the usability of the hypermedia maintenance information system in three particular respects:

1. The ease with which users learned how to use the system.
2. How satisfying the system is to use.
3. Whether the system contains the functionality required by users.

By the time of the trials, the Acrobat One system had been available to team members near Operation 110 for 8 months. The trials described below were the first such trials carried out with the users, although due to production pressure many of the sample of 18 users were actually from another area of the factory, and had never used the system before.

5.21.1 Design of tests

The trials, which had been piloted at Cranfield, took the form of several small tests in which users were asked to find information using the hypermedia system. Users were each given approximately five minutes training to become familiar with the user interface and the structure of the system, and then they were timed as they attempted each test. The tests are included as appendix C. After each test users answered a set of simple questions that were designed to evaluate system usability in terms of three factors:

1. Ease of use.
2. Perceived usefulness.
3. Users' intention to use the system in the future.

Users were also asked to record any other reactions, impressions or comments about the system. Before commencing the series of tests, users answered several questions about themselves. These were designed to evaluate the test subjects in terms of three factors that might have influenced their performance in the trials:

1. Whether the subjects had used the system whilst it was available in the factory.
2. Whether they used a personal computer at work or home.
3. Whether they considered the identification of spare parts to be part of their normal duties.

Another set of questions was designed to test subjects' levels of 'computer anxiety'. It was felt that this construct might also affect their evaluations of the system. The resulting user profiles and the results of the trials are given in chapter 6.

5.22 Demonstrations Using Acrobat Hybrid Application

The Acrobat Two system for the new assembly machine incorporates the lessons learned in the usability trials. Although this application is incomplete (having no stock lists), it was installed on the PC next to the assembly machine since the Acrobat One system is no longer any use to the Ford team workers. This means that users can at least learn about the new machine from the drawings, pictures and animated sequences.

A hybrid application known as *Acrobat Hybrid* was created that was intended for demonstration purposes only. This was based on the Acrobat Two system but it included the stock lists and certain drawings from the old Acrobat One system. In addition to the scheduled maintenance system (SMS) information included in the Acrobat One system, the Acrobat Hybrid system included more FTPM information such as:

- A set of 'single point lessons'.
- A hypermedia flow chart to help team members to fill in the fault reporting tags.

5.22.1 Single point lessons

Part of the FTPM methodology is the use of small group activities to spread good practice within the teams. Examples of good practice are documented in graphical form and displayed on the shop floor as single point lessons (SPL). If a team member has particular knowledge about a process and its likely failure modes, this knowledge can be shared with other team members through the use of single point lessons. In Bridgend, SPLs are usually prepared using Microsoft PowerPoint. The resulting files may be converted to PDF directly using the 'PDF writer' software that is part of Acrobat Exchange. It is therefore extremely straightforward to include SPLs in the Acrobat hypermedia application.

There are several advantages of the hypermedia approach to SPLs over the paper version:

- There is no limit to the number of hypermedia SPLs that can be displayed through the computer.
- Hyperlinks can be used to link SPLs to the relevant machine or machine systems. They are then read in context.
- Hypermedia SPLs can be indexed so that they can be found using a text search.
- If the hypermedia application is accessed via a network, it is very much simpler to arrange issue control of SPLs.
- Hypermedia SPLs cannot be damaged or removed without permission.

5.22.2 Demonstrations within Ford

This application was used to demonstrate the principles of an Acrobat hypermedia maintenance information system to the following groups within Ford:

- Ford systems group at Warley.
- The Bridgend Reliability and Maintainability (R&M) committee.
- The Ford Reliability Forum at Dunton.

5.22.3 Demonstrations to manufacturers outside Ford

The eighth step of the research methodology was to test the applicability of the hypermedia maintenance information system outside Ford. This was done through demonstrations of the Acrobat Hybrid application to representatives of three manufacturing organisations. Representatives from each organisation were interviewed to determine their attitude to maintenance information systems in general and the hypermedia approach in particular. Two of the organisations questioned were chosen for their proficiency in maintenance as shown by their performance in DTI sponsored AMIS audits of their maintenance activities (Jones, 1994). The third organisation is not known for proficiency in maintenance but was chosen to see if the value of hypermedia might be generally apparent. The individuals and organisations interviewed were:

- Paul Sands who is the Operations Director at James Halstead Ltd, one of the world's leading flooring manufacturers. James Halstead Ltd is a TPM user whose plant in Manchester scored 70% in an AMIS maintenance audit.
- Melvyn Slater who is the Engineering Manager at the Norwich depot of Britvic Soft Drinks Ltd. Britvic is part of the Bass Group and their depot at Norwich manufactures the Robinsons brand of soft drinks. The Norwich depot scored 88% and 77% in AMIS audits in 1994 and 1996 respectively. Melvyn was interviewed with two colleagues who maintain Robinsons' equipment.
- Gary Green who is the Engineering Manager at Essex International Ltd, a US owned manufacturer of copper wire whose plant in Merseyside was formerly part of the BICC Group. The plant in Merseyside manufactures copper wire in a range of different gauges, which is then enamelled and supplied for use (typically) in the armatures of DC motors. Maintenance is recognised as a vital activity since high levels of unplanned maintenance severely restrict output.

The main questions asked in the interviews are shown in appendix E and a transcript of each interview in appendix F.

5.22.4 Demonstration to a manufacturing system supplier

One of the delegates at the Ford Reliability Forum was Mr Philip Lawson, the R&M Supervisor from Giddings & Lewis, who supply transfer machines for Ford's engine machining lines. He explained the R&M philosophy at Giddings & Lewis and revealed that they are using Acrobat Exchange to produce digital manuals to support their next generation of transfer machines.

A visit was arranged to their factory and the Acrobat Hybrid system was used to demonstrate the work at Cranfield. Mr Lawson explained that the company is currently obliged by EC law to provide three copies of a paper manual per machine. This constrains the design of their digital manuals to A4 format, which is not ideal for viewing on computer screens. However, they wish to create digital manuals from the same information used to produce the paper equivalent, with minimal extra effort. This is the main reason why they chose Acrobat Exchange.

Giddings & Lewis produce all their drawings using CAD, so displaying them in PDF format is inexpensive since it does not involve scanning. They are also encouraging their suppliers to give them CAD drawings. They use a modular approach to the design of machine tools and between 65% and 80% of their machines are generic. They intend to use video and animation to illustrate operation and maintenance of the generic parts of their machines, for which such material is cost effective to produce. They generate animations for use in sales, marketing and training, so this material is available at no extra cost.

In future, Giddings & Lewis plan to make their digital manuals accessible via a touch screen that would be part of the machine tool itself. At approximately £4,000 the cost of such a screen is minimal compared to the cost of a £4 million machine tool. At present, their digital manuals are to be delivered using CD-ROM, but in future they envisage delivery of such information via the world-wide web.

Following the demonstration of the Acrobat Hybrid system, Mr Lawson commented that the tabs in the user-interface were an effective method of navigating the hypermedia system. He has since been given advice on how to incorporate tabs in his manuals. He agreed that the presence of animated sequences is a particularly effective means of describing complex machine motions. He commented that animations would become easier for Giddings & Lewis to create now that they have started to use solid modelling with AutoCAD in their design process.

5.23 Summary of Chapter

This chapter has outlined the industrial background to the development of a hypermedia maintenance information system at Ford's Bridgend Engine Plant.

The chapter has then outlined the stages in the design process before describing each stage in detail as well as the various information systems that resulted. Early in the development process, the decision was taken to change the authoring tool used, and the reasons for this have been explained.

During the development process, several issues emerged that concerned the presentation of engineering drawings and other technical information in the factory environment. These issues will be of interest to those involved with the development of similar information systems in the future, and they have been described in this chapter.

The reactions of users and managers to each of the information systems developed are described, as are the details of usability trials carried out to evaluate and inform future development of the system. The results of these trials are presented in the next chapter.

The chapter ended with a description of a hypermedia digital manual used by Giddings & Lewis to support the next generation of engine transfer lines for block machining.

6. Evaluation

This chapter describes the evaluation of the system according to steps 5, 6 and 7 of the research methodology. These steps cover the evaluation through usability trials, a cost-benefit analysis and demonstrations to maintenance managers outside Ford. A copy of the usability tests and questionnaires is given in appendix C.

6.1 Results of Usability Trials

The purpose and design of the usability trials are described in chapter 5. The results below describe the user profile and the ease with which they found information using the hypermedia system.

6.1.1 User profile

Before commencing the series of tests, subjects answered several questions so that the results of the trials might be compared with several factors that might be expected to have influenced subjects' performance. The factors considered were a subject's age, prior use of the application, use of a computer at work or home and normal duties. The resulting user profiles are shown in Figure 6-1 and Table 6-1 below:

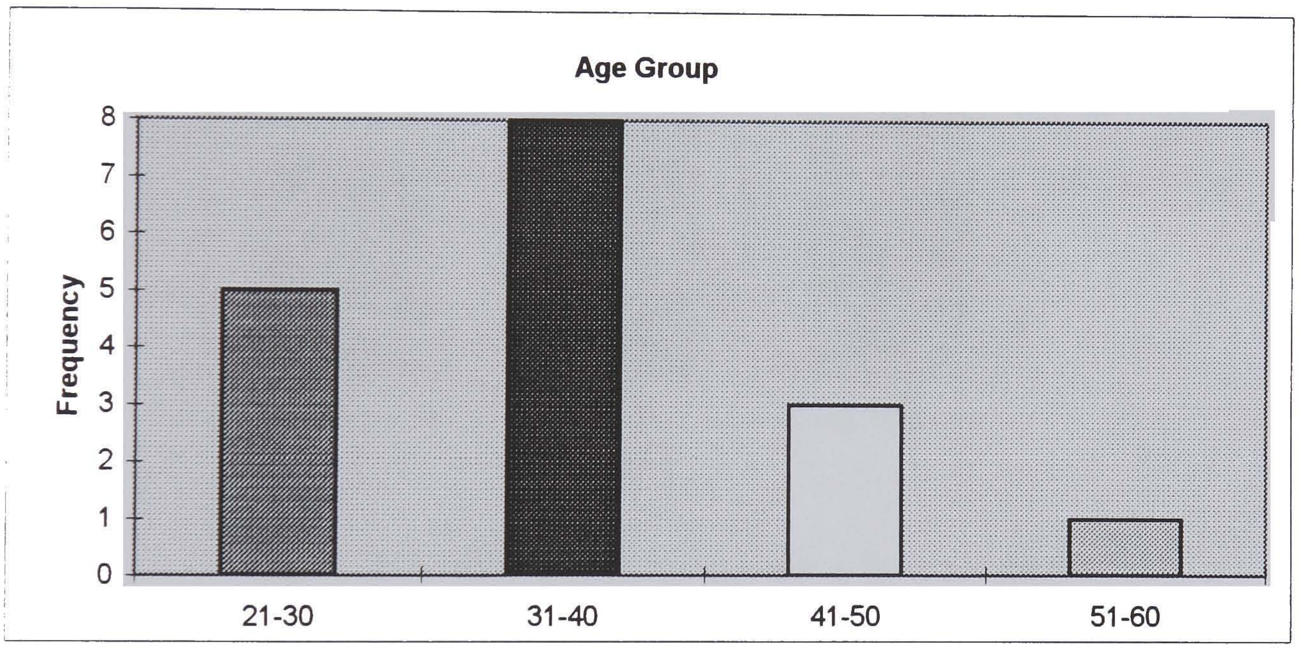


Figure 6-1 Age profile for usability test subjects

	Yes	No
Subject has had prior use of application	3	15
Subject uses computer at work or home	8	10
Subject considers finding spare part numbers to be part of normal duties	11	7

Table 6-1 Factors which might influence performance in trials

Subjects were also asked a number of questions designed to measure their 'computer anxiety'. This was then recorded as either high or low and compared with performance in the tests. The number of subjects who recorded high and low levels of computer anxiety are shown in Table 6-2 below:

	High	Low
Number of subjects with given level of computer anxiety	4	14

Table 6-2 Computer anxiety sufferers

6.1.2 Subjective evaluation of usability

The results of the trials were used to compare the subjective evaluation of system usability between those subjects who had used the system before and those who had not. The results are shown in Figure 6-2 below:

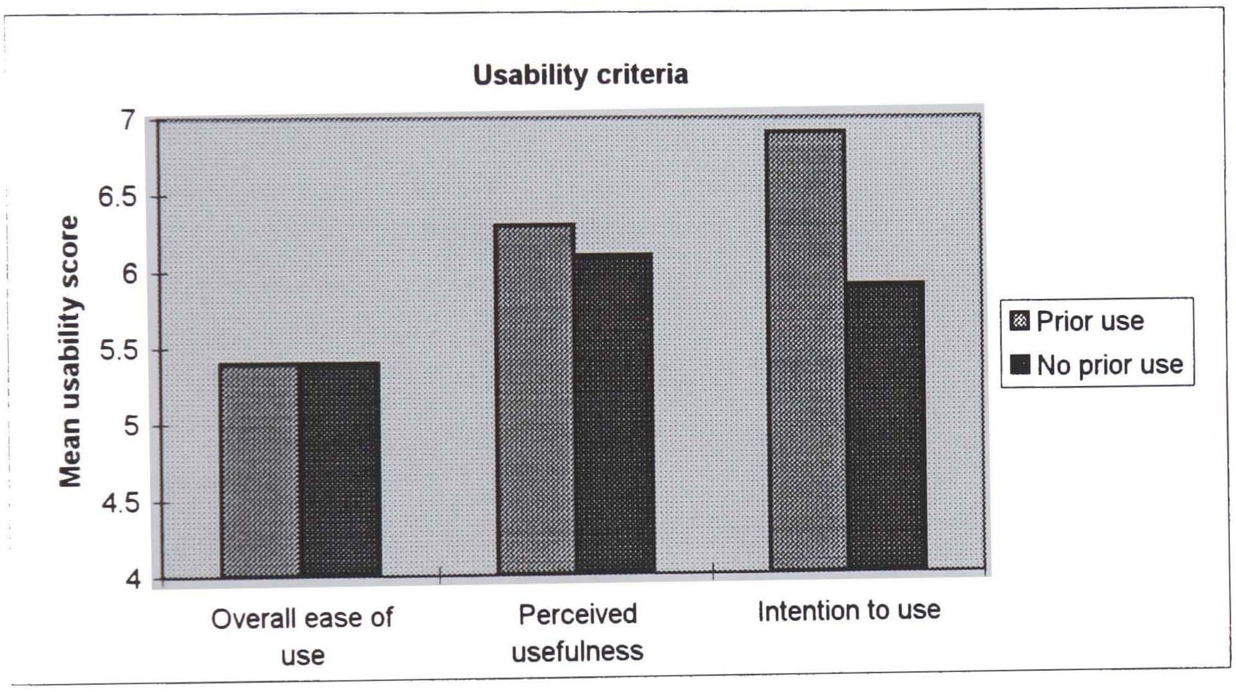


Figure 6-2 Effect of prior use on system usability

In these tests, users were asked to rate the system according to four separate scales, each from 1 to 7 (see appendix C). The results were used to derive the usability figures shown in Figure 6-2, Figure 6-3 and Figure 6-4 where a score of 4 represents a neutral result. There were no scores of less than 4, so each chart shows usability scores of 4 and above.

System usability was compared for those subjects who used a computer at home or work and those who did not. The results are shown in Figure 6-3 below:

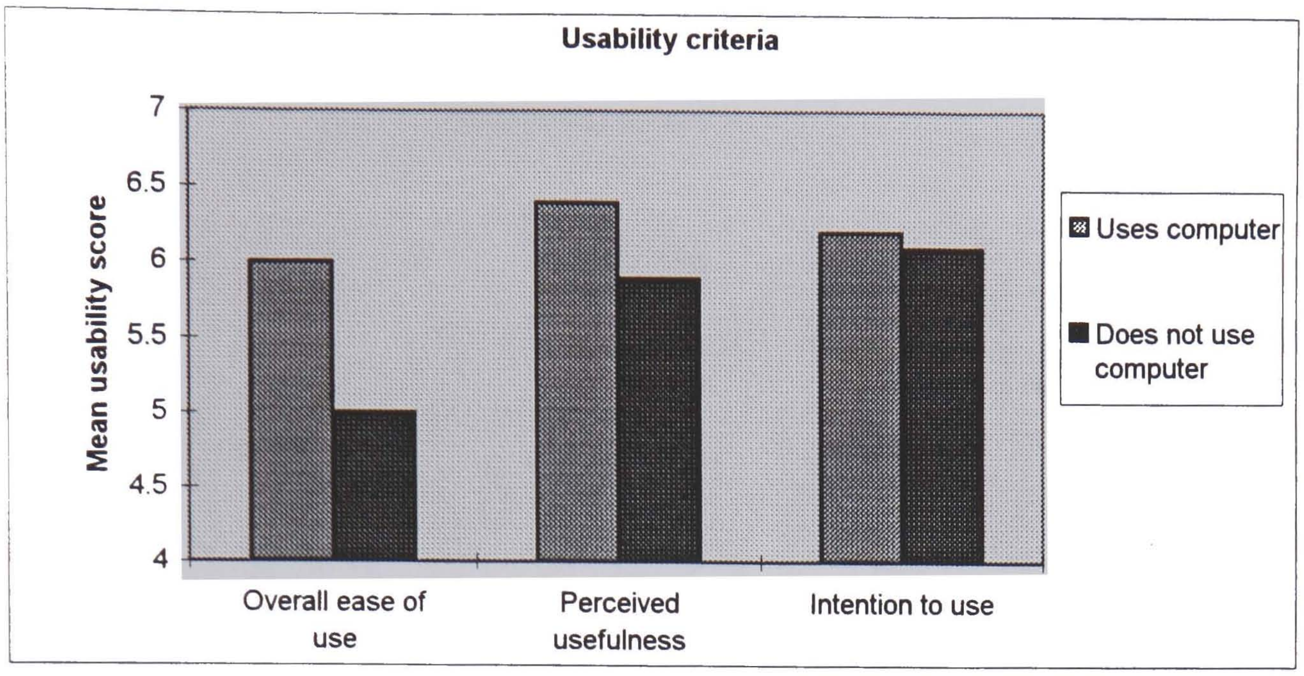


Figure 6-3 Effect of computer use on usability

System usability was compared for those subjects who considered finding spare part numbers and spares availability to be part of their jobs and those who did not. The results are shown in Figure 6-4 below:

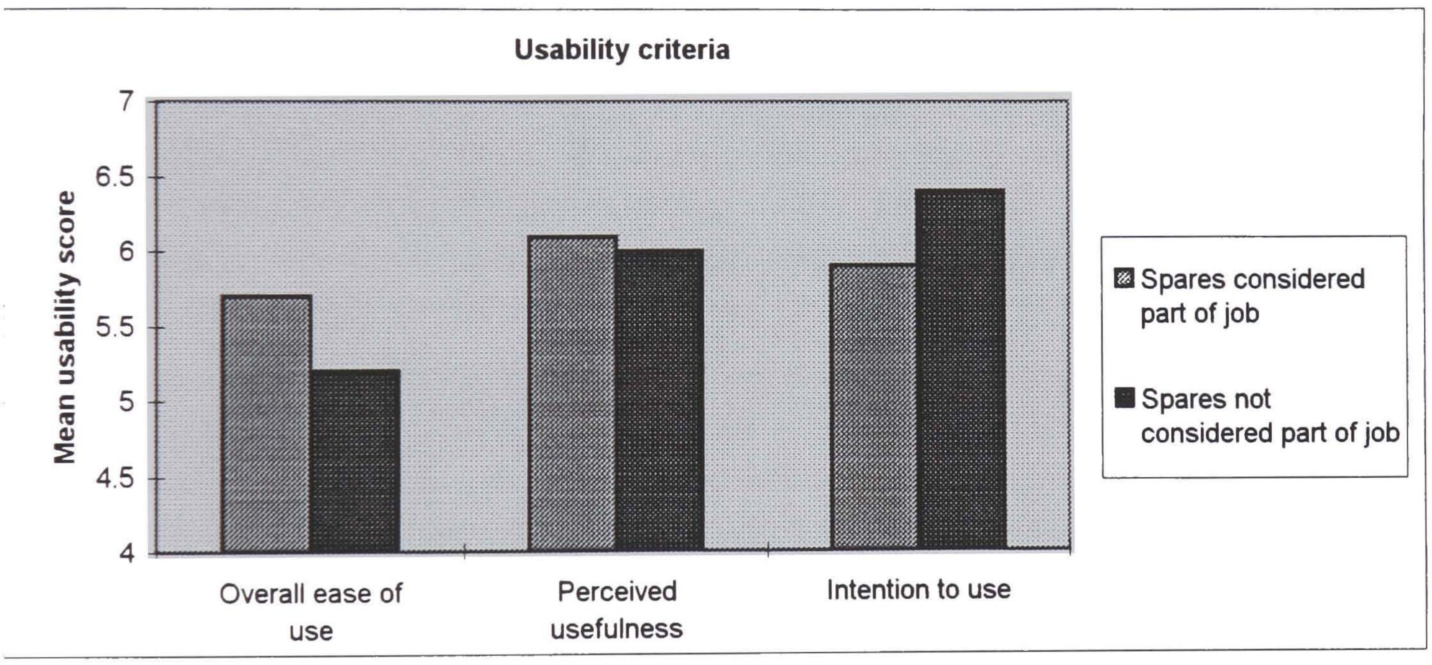


Figure 6-4 Effect of perception of job on usability

Users' evaluations of overall system usability were compared with their individual computer anxiety levels. The results for each subject are given in Figure 6-5 below:

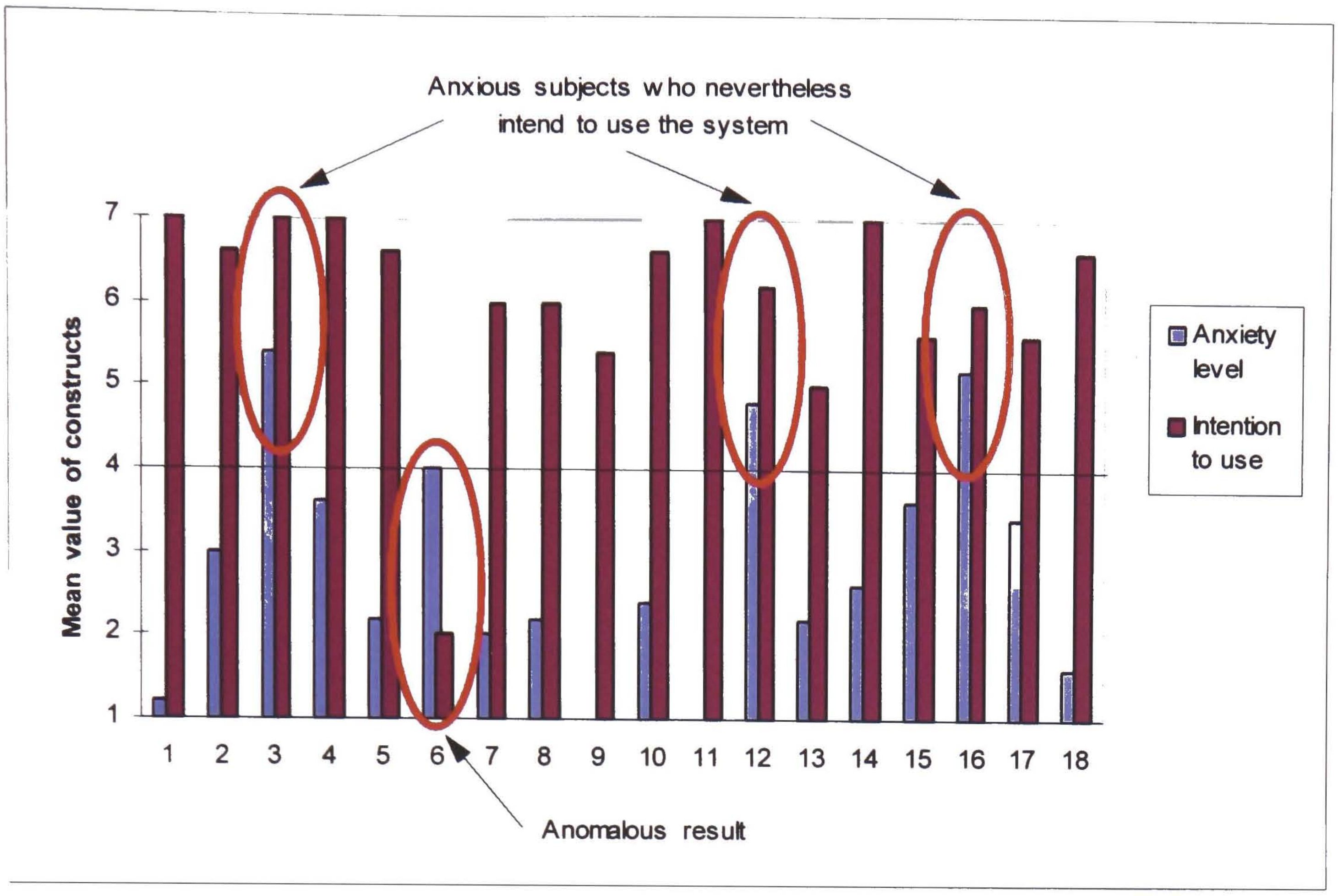


Figure 6-5 Computer anxiety and intention to use for each subject

In figures 6-2 to 6-5, the reference value of 4 signifies ambivalence for the constructs *Ease of Use*, *Perceived Usefulness*, *Intention to Use* and *Computer Anxiety*. Figure 6-5 illustrates the result shown in Table 6-2, which is that most subjects had a low level of computer anxiety. For those subjects with high levels of computer anxiety (i.e. subjects 3, 12 and 16) the subjects reported that they still intend to use the system.

An anomalous result was found for subject 6 who recorded a computer anxiety level of 4 (ambivalent) and recorded a low intention to use the system in future. Although this subject correctly completed all the tests, he commented that "Parts of the program and steps are unclear, but with use may have a function within the maintenance department as a backup to existing systems". Not all subjects chose to comment, but a more typical comment from a first time user of the system was "At first I did not think this would have any relevance to my job, but having used the program I would use it in conjunction with my work".

6.1.3 Time taken to complete tests

As well as the subjective evaluation of usability, some subjects were timed as they attempted the tests. This was done to derive an approximate measure of performance that might be compared with the existing methods of information retrieval. The test subjects had only been given five minutes to become familiar with the application before the trials, and 8 subjects asked for help during the tests. In these cases, a researcher would prompt a subject since it was felt that help would be available for new users of a full-scale system. However, the times taken by these 8 subjects were not used for this part of the usability trials.

These results for the remaining 10 of the 18 subjects who did not require help are shown in Table 6-3 below:

	Time (seconds)				Valid observations
	Mean	Maximum	Minimum	Std. Deviation	
Scenario 1	165.4	260	69	53.8	10
Scenario 2	32.1	75	9	20.7	9
Scenario 3	75.1	164	21	45.7	10
Scenario 4	137.8	269	55	84.9	10
Scenario 5	113.1	150	59	35.3	9
Scenario 6	162.6	248	78	52.4	10

Table 6-3 Times taken to complete each test scenario

Care should be taken when interpreting the results of this study. This is because some participants mentioned that some of the scenarios were not realistic and were in some way simplified. The test scenarios were designed so that as far as possible, information retrieval would not be a trivial exercise and a certain degree of probing would be required to find the right answer. Attempts were made to duplicate the shop floor situation and for this reason some of the test scenarios followed on from the previous scenario. The reason for the wide variation in times is that some subjects, who did not mind typing, preferred to use Acrobat's text search feature since this allowed much more rapid identification of spare parts than the use of the hyperlinks.

The values of the three usability constructs - Overall Ease of Use, Perceived Usefulness, and Intention to Use were analysed after the tests. The mean values of each of these constructs is significantly higher than 4 (the ambivalent feeling). The technology acceptance model (TAM) indicates a strong theoretical correlation between Ease of Use and Perceived Usefulness as well as between Perceived Usefulness and Intention to Use (Davis, 1993). If this theory is correct, then these results indicate that a hypermedia maintenance information system like the Acrobat One system would be accepted and used by the integrated manufacturing teams at Ford.

6.1.4 Design shortcomings

During the trials, some of the shortcomings of the pilot hypermedia system became obvious. The most serious ones were:

- The text in some tables was too small for one of the older users.
- If tables or drawings continue over two or more pages, this must be clearly indicated.

- If a table or drawing is the last one in a series, this must be clearly indicated.
- If a table extends beyond the first page, column headings must be duplicated on the subsequent pages.

It became clear that hypermedia authors must find a compromise between the amount of information to be placed on one page and the number of pages used. Until the usability trials, the application had contained too much information on too few pages.

6.2 The Benefits of Hypermedia Maintenance Information

There are benefits associated with information technology in general and CMMS in particular. Primrose *et al* (1995) associate improvements in scheduling efficiency, reductions in clerical and administrative labour and more rapid diagnosis of failures with MMIS. Primrose *et al* disagree with those who treat the benefits of maintenance improvements as if they were intangible. They describe a method by which such benefits might be made tangible and included in a cost-benefit analysis.

A far simpler approach is taken here since it is believed that the downtime savings alone might justify the cost of the hypermedia system, so that any further benefits would be a bonus. These further benefits are described, although they are not quantified. The downtime reductions possible through the use of hypermedia are assumed to derive mainly from reductions in the time taken to retrieve relevant information in a breakdown situation.

6.2.1 Ford data used in analysis

Ford's Bridgend Engine Plant is not treated as a profit centre since its products are sold internally. Cost savings are therefore derived from reductions in labour and overheads associated with reductions in overtime. Overtime is needed to manufacture engines that could not be made to Ford's schedules, the main reason for this being breakdowns. The analysis starts with the cost of breakdowns across the whole of the Zetec assembly line. Ford's Industrial Engineering Department at Bridgend estimates this figure to be $2.58 million per annum.

6.2.2 Downtime reductions through faster access to information

For the purposes of this analysis, a hypermedia information system is assumed to influence the downtime associated with information retrieval. Further benefits are discussed after the analysis.

Zetec assembly workers estimate that between 5% and 80% of total breakdown time represents those stoppages that require spare parts. Because of the wide variation, an average figure of 13% was suggested by Ford industrial engineers. Zetec assembly workers estimate that out of these breakdowns, approximately 67% of their time is spent looking for information required to identify the part and its stores reference number. This is the proportion of downtime that may be reduced by the hypermedia information system. The relationship between lost time and the total time available is shown in Figure 6-6.

6.2.3 Downtime savings through the use of hypermedia

The amount by which breakdowns might be reduced through the use of hypermedia can be estimated by comparing the times recorded during the usability trials with estimates for similar searches using existing techniques. Five of the six test scenarios in the usability trials involved the identification of spare part information. Averages of the times taken by users during the five relevant tests are given in Table 6-3. Although some users took advantage of the search feature to record a much faster time than those who used the hyperlinks only, it is felt that with experience all users should be able to match the average times for each test. These average times were averaged to estimate the time taken to identify a typical spare part using the hypermedia system. This time is 115 seconds.

Team members on the Zetec assembly line at Bridgend estimate that most spare part searches currently take between 5 minutes and 30 minutes. If the user-interface to the stores database were improved to match the best system of this type, one might assume that all team members could achieve an average figure of 12.5 minutes or 750 seconds. An estimate of the savings available through the use of hypermedia information systems similar to the Acrobat One system is therefore 750 – 115 = 635 seconds. This figure represents a reduction of 85% (see Figure 6-6).

Figure 6-6 also shows how the application of information systems like the Acrobat One system could increase the output of the Zetec assembly line. The magnitude of the yearly benefit can be estimated by multiplying the percentages shown in Figure 6-6 by the cost of annual breakdowns calculated above:

Estimated benefit = 85% × 67% × 13% × $2.58 million = **$191,010** per annum.

6.2.4 Sensitivity analysis

Because of the wide variation in estimates of the proportion of breakdowns needing spare parts and the time taken to search for such spares, a sensitivity analysis was carried out. The highest and lowest estimates of savings are derived by varying the proportion of breakdowns needing spare parts, the time currently taken to locate these spares and the time taken to locate the spares using the hypermedia system. The figures used and the results are shown in Table 6-4.

	Proportion of breakdowns needing spares (by time)	Time currently taken to search for spares	Time taken to search for spares with hypermedia	Estimated annual savings
Lowest estimate	5%	5 minutes	203 seconds	$27,660
Highest estimate	80%	30 minutes	46 seconds	$1,341,400

Table 6-4 Lowest and highest estimated savings through the use of hypermedia

6.2.5 Discussion of savings calculations

Because of the difficulty of obtaining accurate figures, the analysis above contains many estimates and assumptions. These have been indicated in the text. There are other ways to calculate such benefits but the one chosen is based on methods used by Ford. As well as the final estimate of the benefit, the means by which the benefits are derived is important. This analysis may be used to focus management effort on understanding both the causes of downtime and how better access to information can reduce the cost of downtime.

In addition to the estimated savings for Zetec assembly, there would also be savings on the Jaguar and Zetec SE assembly lines and the machining lines for all three engine programmes. Indeed Ford engineers indicate that the savings on machining lines are likely to be higher than on assembly lines due to the nature of the machines and their failure modes. These savings would be in addition to the savings calculated above with no increase in the cost of information system maintenance since Ford engineers assume that one person would be able to maintain the information system for all lines in an engine plant.

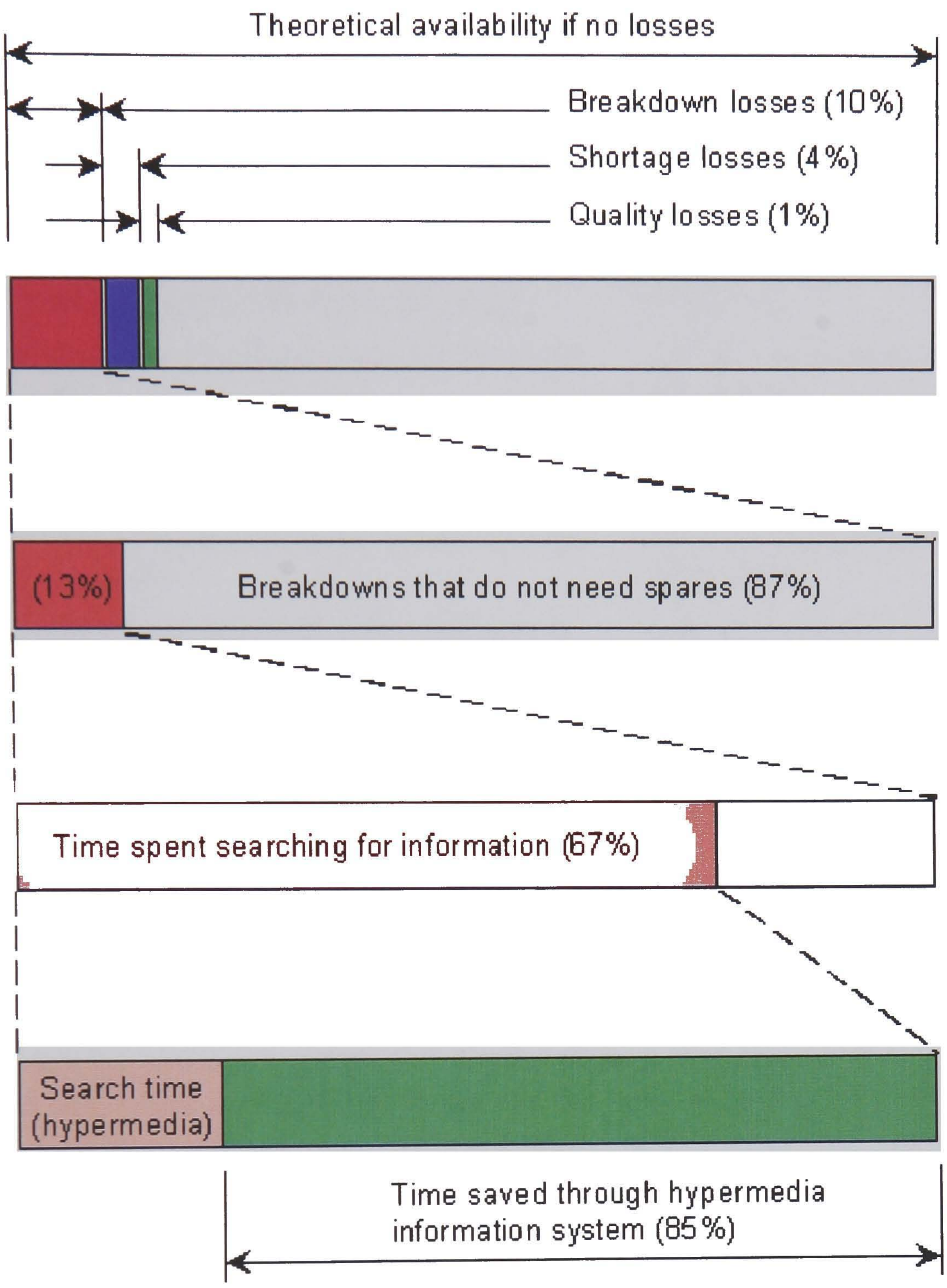


Figure 6-6 Time saved through use of hypermedia information system

6.2.6 Other benefits of hypermedia maintenance information system

The additional benefits of the hypermedia maintenance information system, which have not been quantified, are shown in Table 6-5 below:

Feature of System	Benefit
Empowerment of semi-skilled workers to find spares, which allows skilled workers to focus on more demanding tasks.	Increases maintenance productivity. Increases motivation.
Empowerment of workers allows maintenance co-ordinator to focus more on strategic issues.	Better maintenance planning.
Improves understanding of process through animations and easy access to drawings, pictures and other documents.	Increases maintenance quality. Fewer breakdowns.
Shared knowledge through repository of single point lessons. and PM procedures.	Increases maintenance quality. Fewer breakdowns.
Forms a repository of illustrated PM procedures.	Better quality PM tasks leading to reduced life-cycle costs.
Simpler control of revisions since data can be held on server and accessed over network.	Reduced overheads. Increased quality of information.
Digital storage replaces aperture cards readers and printers.	Reduced overheads.
Can be used as part of training programmes.	Better knowledge retention through interactive media.

Table 6-5 Benefits of hypermedia information system that are not quantified

6.2.7 Cost of providing hypermedia information systems

The cost of producing the pilot hypermedia information system does not reflect the likely cost of producing a full-scale system to a similar design. The cost of such a system comprises the preparation cost of the media and the cost of adding the hyperlinks. By far the most cost-effective method of authoring a digital manual is to prepare the media and add the hyperlinks during the design and build of the product (in this case a complex assembly machine).

With the exception of the animated sequences, the media need not cost any more than at present. When EC law permits, there will probably be a cost saving since it will no longer be necessary to print and bind several copies of a paper manual. The costs of storage, distribution and maintenance of digital manuals can be assumed to be lower than for paper equivalents. It may only be cost effective to include animated sequences if they had previously been prepared for sales purposes or if solid modelling had been used by the machine supplier as part of the design process. This is the case at Giddings & Lewis, whose transfer machines are used in Ford's engine machining lines.

When questioned on the cost of digital manuals, the R&M Supervisor at Giddings & Lewis said that although the production of digital manuals adds extra cost at present, in future the cost would fall for two reasons:

1. Technical writers in the company would become more familiar with their production and better equipped to provide the media and add the hyperlinks.
2. Graphical communication methods would replace much of the text used in paper manuals.

Ford already owns the hardware and network infrastructure necessary to make one copy of a digital manual available throughout the global organisation. This means that the only cost to Ford would be the cost of the maintenance of the manual. As this thesis has shown, hypermedia manuals can act as a repository of process knowledge that is gained as a work force gains experience of a new process. This knowledge could be expressed as single point lessons that could be added to the relevant manuals by a designated individual. This could be done globally or on a plant by plant basis, but the validation of this information has no additional cost since it is carried out as part of the FTPM process. The only cost would be the cost of the salary of the individual responsible for maintenance of the digital manuals.

6.3 Presentations to Ford Managers

Following presentations to the Ford staff in the UK such as the Bridgend Reliability and Maintainability (R&M) committee, the Systems Group at Warley and the Ford global Manufacturing Facilities Reliability Forum at Dunton, a demonstration was carried out for Mr Russell Louks. Mr Louks is in charge of maintenance systems in Ford's Manufacturing Systems Office in Dearborn. He commented that the Acrobat hypermedia application (or something similar) might be suitable for incorporation into TEM - Ford's global maintenance system. He also recognised the following advantages of the Acrobat application:

- It is simple.
- Acrobat Reader is free.
- It is easy to distribute.
- Ford plants can easily create their own media.
- A bigger study of the approach would not be an expensive experiment.

Mr Louks has asked for a presentation of the system to a TEM user group meeting at Ford's Rouge Offices in Dearborn.

6.4 Visits to Companies for Interviews and Demonstrations

The Ford hypermedia system was demonstrated to maintenance managers from three companies outside Ford, who were interviewed in a semi-structured manner about their maintenance practices and their views on CMMS in general. The interviewees were also asked for their feelings about the possible application of a hypermedia maintenance information system like the Ford pilot system in their organisations. The interview questions are shown in appendix E and the transcribed interviews are included in appendix F. The edited results of the interviews are below.

6.4.1 Interview with Paul Sands of James Halstead Ltd

A CMMS is in use at James Halstead and this is integrated with their 'Movex' manufacturing system that also controls the spare parts inventory. When spares are issued from Movex, this is reflected in the CMMS. The CMMS allows users to report breakdowns by selection from a list of standard breakdown descriptions. They are expected to enter text descriptions of breakdown solutions but the company has difficulty getting their craftsmen to use the system. In practice they write what they do on paper and their team facilitators type these reports into the system. Technicians from the Engineering Support department support the craftsmen, and if they provide a solution to a breakdown they are expected to enter it into the CMMS. The company is currently considering whether to abandon the CMMS and to adopt a CMMS module of the Movex system. This is because of the superior usability of Movex, and the problems experienced by users when moving between the two systems.

Technicians with electrical skills support the electronic control systems where most unplanned maintenance is needed, and a mechanical technician tends to get involved in continuous improvement activity. Maintenance craftsmen have been specially trained so that they are considered to be multi-skilled. They report to production and are members of teams that also include machinery operators. Operators carry out PM tasks, cleaning and tagging. If they can, they will fix problems; otherwise they ask the craftsmen. Integration is proving to be slow and difficult. In some areas, it is better than others. A facilitator organises each team.

If an engineering drawing is required, this is found in the Project Engineering Department, where all drawings are stored. James Halstead uses AutoCAD and most of their recent drawings are in this format although many plans are still on paper. As part of the tendering process, they ask their suppliers to provide AutoCAD drawings. Craftsmen do not generally use drawings; instead they rely on their experience. However, if they do need a drawing, for example to order a spare part from the stores, it is printed out rather than viewed on a monitor. Most users of drawings are the technicians from Technical Support, so access to drawings is not usually a problem.

Planned maintenance schedules are printed from the CMMS on a weekly basis and are used as a checklist. PM compliance and TPM compliance information is entered into the system upon completion of each task. These tasks are not supported by any graphical or pictorial information at present, but TPM manuals are being developed in which diagrams and drawings are used to illustrate procedures. Although the company would like operators and craftsmen to provide this type of information, there are difficulties in getting these people to use the computer so a small team is being set up which will do this. At present, the company neither uses multimedia information nor has any plans to do so.

The two most important improvements which James Halstead would like to make to their maintenance activities are firstly to change the focus of the Technical Support department from breakdown maintenance to preventive maintenance including FMECA, and secondly to manage their craftsmen more effectively in the teams. One of the aims of the PM activity is to get craftsmen more involved with the teams.

6.4.2 The relevance of hypermedia to James Halstead Ltd

The company is keen for those involved in maintenance to document their own work, for this to be achieved with as little authoring or maintenance effort as possible and without setting up a separate department. The value of a hypermedia system that was both simple to author and accessible over a network was clearly recognised. The structure of the Acrobat Hybrid system was appreciated since it allowed a user to drill down from the plant to component. One problem with the Acrobat system is not being able to access the information right next to the work. The system should allow a user to print out a drawing.

The environment at James Halstead was felt to be unsuitable for laptop computers or personal digital assistants (PDA), although these might be considered if they could also be used for data capture. The value of the information that could be passed back to the organisation might be such that investment in PDAs could be justified.

The company produces a variety of operational information such as quality manuals, environmental procedures, training and development notes and health and safety manuals. All their procedures are documented on paper but are not necessarily useful to the shop floor. Using paper, the company can easily end up with two sets of documentation, the official procedures and the 'quick guides' that are accessible to the people on the shop floor. Hypermedia could solve this problem by presenting plant operation in a more accessible format with the detail hidden from the casual reader, but easily available through hyperlinks. At James Halstead, such information would be accessed over their network via Lotus Notes.

6.4.3 Interview with Gary Green at Essex International Ltd

There is no CMMS in use at Essex, but there is a vibration analysis system. PM tasks and frequencies are listed in a spreadsheet although there are no task descriptions as such. Fault descriptions and solutions are recorded on paper and it is accepted that the company would benefit from a CMMS. Important benefits of a CMMS are perceived to be more rapid access to information during breakdowns and the construction of a database of common faults and solutions. This database would function as a knowledge repository that would be of use to the majority of workers who do not share the expertise of a few.

At present, an operator informs the shift manager in the event of a breakdown. The manager fills in a problem report sheet that is handed to the maintenance department. This sheet may join other sheets to form a pool of tasks with no priority for maintenance to work on. The shift manager decides priorities, which can lead to maintenance craftsmen being taken off a job before it is complete and assigned to a more recent job that is felt to have a higher priority. The maintenance manager would like production workers to use a computer network to report faults directly into the maintenance department, which would eliminate the paper forms. He would also like to assign priorities to certain tasks. The system would also be used to inform the shift manager which task had been completed. At present, it is sometimes the case that completed tasks are not reported to the shift manager as soon as the plant is available again.

At present, all engineering drawings are held in the engineer's office on paper. It is time consuming to look through these to find information about spare parts. Since craftsmen take the master drawings with them if they need to use them during maintenance, the drawings are deteriorating. It is intended to study the planned maintenance activities with the aim of reducing the amount carried out. It is felt that the current level of PM activity is excessive and approximately 25% of tasks are of no real benefit.

6.4.4 The relevance of hypermedia to Essex International Ltd

If the information could be located and provided in the right format, the main benefit of a hypermedia maintenance information system would be the availability of a complete set of documentation. An example of a situation where this could be useful is a description of condition monitoring tasks. A hypermedia system would provide many benefits over the current paper driven maintenance system, which is very time consuming. The hypermedia system demonstrated does actually mirror the information search that a tradesman goes through when trying to identify a bearing (for example) at Essex. The hypermedia system would therefore save a lot of time as well as allowing others besides the tradesman to search for a spare part.

It was pointed out that some managers at Essex would be cynical about hypermedia and that the company would need to familiarise its operators with PCs, particularly the older workers. However, the newer machines have advanced controllers such as SCADA (supervisory control and data acquisition) systems and the operators of such machines are already familiar with computers. Here, the operators have already successfully been given responsibility for some maintenance and it was felt that hypermedia would be accepted by them. On the older machines with less skilled operators this might not be the case.

For a hypermedia maintenance information system to be of benefit to Essex, there would need to be a link to the stores database, but it would be very useful to record lessons learnt during maintenance and make these available via the system. The resulting hypermedia system is seen as a kind of human-centred expert system that would allow all workers to share the expertise that they develop.

Although it was felt that the Ford hypermedia system was an excellent idea, the real problem for Essex would be the time taken to author the content. This would require an individual to spend a considerable time gathering data and linking it in a meaningful way. It was estimated that this could take three months but the effort might well be justified through reductions in breakdowns.

6.4.5 Interview with Melvyn Slater and two craftsmen at Robinsons

Robinsons used a Hoskyns CMMS in the 1980s but this was replaced by a 'home made' system in 1995 when the company was bought, and central support for the Hoskyns system ceased. The maintenance department then decided that they wanted a system to suit them instead of one specified by systems analysts, so they wrote their own simple system based on Excel (for stores inventory, plant care and procedures) and Access (which forms a plant history database). In fact, by then the Hoskyns system was mainly used to control the spare parts inventory, and little else. Robinsons adopted TPM in the early 90s and maintenance is now operator-based rather than engineer-based.

Two sets of plant performance information are collected on paper. Line operators collect one set and maintenance engineers collect the other set. An administrative assistant enters both sets of information into the Access database. The information is then used to generate reports on plant history and plant performance.

Maintenance information such as equipment manuals, drawings etc. is stored centrally in the workshop, although there are also 'centres of excellence' around the factory which contain information relevant to particular machines. Drawings are stored on paper and if a drawing is needed at a machine, the master copy is usually taken. Planned maintenance task descriptions are generally text documents with no graphics or pictures, although lubrication procedures are illustrated using PowerPoint slides that contain digital photographs.

It was felt that Robinsons' approach to CMMS could be improved by integrating the separate information systems used. Typical benefits of an integrated approach would be the automatic ordering of spares and the automatic generation of plant care instructions based on run hours.

6.4.6 The relevance of hypermedia to Robinsons

The main benefit of a hypermedia system such as the one demonstrated was felt to be the time saved when looking for information. In many ways, the Ford hypermedia system is a computerised version of what Robinsons use already, except that Robinsons has more information such as lubrication instructions and quality checks on goods produced. The simple structure of the information in the hypermedia system was felt to be useful.

The particular benefits of the use of a computer in this way are seen as the way that one can store a very large volume of information centrally and yet still access the required information quickly from anywhere with access to the network. The maintenance manager liked the realism of the animation and the general look of the system.

One of the craftsmen with experience of computer graphics (but not Acrobat) commented that the Acrobat information system seemed to be easier to author than systems he had experienced so far. The flexibility of the Acrobat hyperlinks was appreciated, but it was pointed out that Robinsons would need more than a read-only system. They would need to be able to use the system for data collection as well.

It was recognised that Acrobat could help Robinsons achieve the integrated approach to maintenance that they need. It was felt that one should regard the Ford hypermedia system as a general manufacturing management system rather than simply a maintenance management system. This was because the hypermedia approach could be used to integrate information for training and operation as well as asset care. The Robinsons best practice manuals actually have very similar structure and content to the Ford hypermedia system. One possible approach to hypermedia authoring at Robinsons would be to use the system to annotate drawings with notes about known problems with certain components and systems. These problem descriptions could also be linked to known solutions.

It was pointed out that one problem with the Acrobat system is the need for PC skills. It was felt that this could be mitigated by the use of voice input as a means of rapid data entry, but it was also felt that operators at Robinsons might not be happy wearing or using a microphone. It was then suggested by Mr Slater that the ideal solution might be the provision for data collection by voice as one option among others, depending on user preference. An observation about the current generation of CMMS software was that users must alter their behaviour to suit the system whereas the ideal system would adapt to suit the user.

6.5 *Summary of Chapter*

This chapter has described the evaluation of a pilot hypermedia information system that was produced using Acrobat Exchange from Adobe. The system was evaluated using a combination of usability trials, a cost benefit analysis and demonstrations to maintenance managers in other organisations besides the sponsor.

The results of usability trials indicate that the system is easy to use, it is perceived to be useful and that team members intend to use it.

The cost-benefit analysis showed that a hypermedia information system of this type is likely to be cost-effective. Although the analysis is based upon estimates of the impact of more rapid access to information upon downtime, the estimates were conservative. Further benefits were described, although these were not quantified.

Lastly the interviews with maintenance managers indicated that in three different organisations not connected with the automotive industry, a hypermedia information system of the type demonstrated would be useful, with certain provisos. These were that the system should be:

- Integrated with the stores database.
- Linked to a printer.
- Enhanced with data capture functions to allow the input of fault descriptions and solutions and the recording of planned maintenance task completion.
- Expanded to include more information besides that used for maintenance. Examples are quality information, health and safety information and test procedures.

Those interviewed felt that the main benefits of the system were faster access to information that can be expressed in a very usable form and the formation of a repository of maintenance knowledge, which can be updated by the work force.

7. Discussion and Conclusions

This chapter briefly summarises the main lessons drawn from the literature and relates these to the research hypothesis. The extent to which the research supports the hypothesis and the contribution made to knowledge are then discussed. The particular advantages of the PDF information format are then discussed followed by recommendations for readers who intend to create digital manuals. Lastly, examples are presented of future research based on the work described in this thesis.

7.1 Summary of Research

This thesis is concerned with the application of information technology to team-based maintenance. Research has been carried out in an engine plant belonging to the Ford Motor Company where TPM is practised. The literature review identified three types of information system that can be used to reduce the cost of maintenance. These are CMMS, diagnostic systems and digital manuals. Each can be used in a TPM environment although the literature indicates that they may not be equally suitable. These three techniques need not be seen as alternatives since they can complement each other. However each type of system is designed for a different type of user and a different type of maintenance activity.

7.1.1 TPM in automotive manufacturing

TPM has been shown to be a highly effective approach to maintenance of complex processes used by automotive manufacturers. Developed by the Japanese and first introduced in the Toyota group, TPM is a human-centred approach to maintenance, which emphasises the role of the process operator in asset care, fault finding and continuous improvement. Maintenance of complex manufacturing systems requires the unique ability of humans to identify and comprehend previously unforeseen failure modes, to communicate these and to work with others to eliminate them (Helfgott, 1987). TPM recognises the superiority of humans in the maintenance process and supports both maintenance and production personnel with standardised information such as:

- Planned maintenance procedures.
- Single point lessons (in Ford factories).
- Descriptions of manufacturing processes and their operation.
- Quality manuals.
- Test procedures.

This information is presented in the form of highly accessible documents (usually paper) that are often accompanied by illustrations and are visible near to work centres on the factory floor. In this way TPM uses documentation to improve overall equipment effectiveness. This documentation is often prepared using commonly available technologies such as digital photography, word processors, spreadsheets and presentation software.

7.1.2 Computerised maintenance management systems

CMMS are used for the management of the business processes associated with maintenance, such as activity planning and the control of inventories, costs and the maintenance work itself (Niebel, 1994). Shenoy and Bhadury (1998) have shown how an MRPII system could be used for maintenance management and many ERP systems include maintenance management modules.

Since they were first introduced in the 1970s, CMMS have become cheaper and much more powerful. Many systems offer features that are claimed to support TPM and RCM programmes. However, CMMS have been criticised for their technology-centred design (Raouf, 1994) and doubts have been expressed over their technical benefits (Hipkin, 1997). CMMS are less relevant to the execution of the maintenance function on the factory floor than to its management. This explains Swanson's (1997) results for the low usage of CMMS by production operators. These results, which are echoed by Boznos (1998), imply that CMMS may not be the most appropriate form of information system in the TPM environment, where process operators need access to maintenance information. This does not mean that CMMS should not be used where TPM is practised, but managers should be aware of its limitations and that there may be a more appropriate type of information system to support TPM. Mulcahy (1999) claims that the specialist nature of CMMS makes such software more suitable for maintenance management than generic business systems such as ERP. However the first two tiers of his three-tier CMMS model are threatened by ERP which leaves only the third tier. This is the tier that is configured to suit the needs of users. In a TPM environment the third tier should be a human-centred system that is integrated with the other two tiers.

7.1.3 Decision support systems

Both the management and execution of maintenance involve decisions in situations where mistakes may be costly, dangerous or even fatal. Computers have been used to improve the quality of these decisions using artificial intelligence techniques. However this type of system has been criticised for its inferiority to humans (Clancey, 1993; Jahoda, 1989) and its technology-centred approach (Mitev, 1994). Although the diagnostic systems built into modern process equipment can assist maintenance technicians, it is hard to see a role for traditional artificial intelligence in a human-centred strategy such as TPM. This is because TPM encourages the growth of knowledge as operators become more familiar with manufacturing processes, and this knowledge is shared and used to improve reliability. TPM accepts that much valuable knowledge of possible process failure modes is learned by those involved in daily operation. This type of knowledge is not available in the mind of an 'expert' when the process is designed so that eventually, even the best expert system will be inferior to a trained and observant operator who is supported by a team of skilled maintenance technicians.

However, some writers have described a kind of decision support system which allows the development of a process 'knowledge base' through worker input (e.g. Fischer *et al*, 1996). The way in which the knowledge is structured can be used to simplify fault-finding procedures long after the information has been input. This type of expert system may be better suited to TPM since it seeks to empower a team of problem solvers through shared knowledge, rather than to automate the problem solving process. Many of these human-centred expert systems feature a multimedia user-interface and they represent a type of digital notebook. The main drawbacks of such systems are the effort required to produce them in the first place and the difficulty of maintaining the knowledge base. When a new manufacturing process is installed, the originators of the information contained in a decision support system will be the designers of the manufacturing process. These people are best placed to provide this type of information in a cost-effective manner, so the authoring process must be acceptable to them. The means by which knowledge is added to the system must be acceptable to the process operators.

7.1.4 Digital manuals

The third type of computer system that may be applied to maintenance is the digital manual. These are generally multimedia documents, and they are often hypermedia, which can allow more rapid navigation to the information required. Hypermedia manuals are becoming more common, in the form of interactive electronic technical manuals. IETMs are a feature of the strategic approach to minimising life-cycle costs known as CALS. IETMs have been used to support defence systems and civil aircraft but this type of information system has not yet been seen in the factory environment. Although the maintenance environment in which IETMs are currently used is very different from TPM, the importance of easy access to good quality information is what makes the IETM a suitable tool to support TPM.

Crowder *et al* (1996) describe the use of an advanced hypermedia system called Microcosm to support the maintenance of a manufacturing system. Microcosm permits different groups of users to interact with the same media through different sets of hyperlinks that may be optimised for that type of user. This feature and some of the other features of Microcosm suggest that it is an ideal tool with which to author an industrial digital manual to support TPM.

7.1.5 Development of pilot hypermedia information system

The research methodology involved the creation and evaluation of a pilot hypermedia information system that could be used to support TPM. It was intended to create this system with Microcosm, and the first prototype systems were authored this way. However it was necessary to adopt an alternative means of creating the hypermedia information system, which was to use Adobe Acrobat. This decision meant that the research tool was less advanced in terms of its hypermedia functionality but it was more robust in the factory environment. Acrobat proved easier to use for both authors and readers, but it may be argued that a full-sized system written using Acrobat would be more expensive to maintain than an equivalent Microcosm system. The decision to change from Microcosm to Acrobat did not affect the research hypothesis since both are hypermedia systems. However, the ease with which the pilot system might be extended to produce a full-sized system has been affected. The Acrobat One and Acrobat Two systems used on the shop floor at Bridgend were static read-only systems. Although the Acrobat forms plug-in can be used to turn such a manual into a front end for a dynamic database, this feature was only investigated when developing the Acrobat DC system. A static digital manual can not be considered a replacement for the functions of a CMMS.

If such functions are required in a TPM environment, then the Acrobat systems used at Bridgend must be considered a partial solution only.

7.1.6 Comparison between pilot hypermedia systems and ideal system

Before considering whether the hypothesis is supported or not, it must be considered whether the pilot hypermedia systems developed during this project constitute a representative example of human-centred hypermedia. Table 7-1 compares the Acrobat Two system with the type of human-centred system described in paragraph 4.4.

Successful Human-centred System	Acrobat Two System
Does not constrain users unduly.	User chooses one path from many possible ones via hyperlinks provided by authors.
Allows organisation to leverage the 'tacit knowledge' of workers.	Updates possible by adding PDF files created during team activities.
Does not take longer to author than equivalent paper system.	PDF pages created simply by 'printing' to hard disk. Hyperlinks easily added but time consuming.
User friendly and flexible.	Proven through usability trials.
Aligned with maintenance strategy, in this case TPM.	Contains TPM information in easily accessible form.
Compatible with developments in user-interface technology.	Demonstrated with voice input, touch screen and using laptop computer.
Allows different users to access the information in the system rapidly and in the manner most appropriate for them.	As with a paper manual, does not distinguish between readers but allows choice of navigation via hyperlinks.
Provides information at the site of maintenance.	Information may be directly via network drive, via an intranet browser, from local hard disk or CD-ROM.
They should give access to part stores, production records etc.	Possible using forms plug-in but requires access via browser. This slows viewing and is not considered robust enough for factory users.
Acceptable to a manufacturing organisation with quantifiable commercial benefits.	Benefits quantified. Costs may be too high at present but reducing, whilst cost of paper information increases.

Table 7-1 Comparison between successful human-centred system and pilot system

7.2 *Investigation of Hypothesis*

The hypothesis for this research is that a human-centred information system using hypermedia is an effective means of supporting TPM. This hypothesis has been investigated by designing a pilot hypermedia system that has been shown to have the functions of a successful human-centred system. The use of this pilot system has been studied in a team-based maintenance environment.

A direct investigation of this hypothesis would have required a study of the use of the pilot system to assist planned and unplanned maintenance. Due to the reliability of the sponsor's assembly machine and the lack of support for the pilot information system by the sponsor, this was not possible. The effectiveness of the hypermedia maintenance information system had therefore to be evaluated through usability trials, interviews with Ford personnel and discussions with maintenance practitioners outside Ford.

Any discussion of the effectiveness of information technology to support maintenance invites comparisons with CMMS, and this is done below.

7.2.1 Comparison between hypermedia information systems and CMMS

The hypermedia system developed during this project was a stand alone pilot system that was limited in scope. Its purpose was to investigate the extent to which a full-sized hypermedia maintenance information system might be accepted and used effectively by maintenance and production workers in a factory using TPM.

It might be argued that since a CMMS is not used on the Zetec assembly line and since the pilot hypermedia system gives clear benefits, a CMMS is unnecessary in this environment. However the functions of a CMMS are actually present on Zetec assembly in the form of other business systems. These are the stores database, the scheduled maintenance system and the bubble cards. These systems will be replaced by Ford's global CMMS on the newer manufacturing systems.

There is no doubt that the maintenance management functions of a CMMS are as useful in a TPM environment as in any other. However, this research suggests that these functions do not require a CMMS. A much cheaper generic database or a module of a business system such as ERP could provide them. What the vendors of a simple database or an ERP system cannot provide (and what CMMS vendors do not provide) is the information required for the execution of TPM. Some CMMS allow users to view digital images and engineering drawings in certain formats. In some cases the user must purchase a viewer licence for each seat of the CMMS in order to view drawings. CMMS users and ERP users alike must enter static information such as planned maintenance task descriptions and asset data into the system database during system commissioning. The literature suggests that the population of the database for a CMMS or ERP system is not necessary and is probably a waste of time in a TPM environment, since operators will not use it.

7.2.2 Ability of hypermedia to replace CMMS

The basis of a CMMS is a relational database (Eason, 1997). Although the Acrobat DC system (see paragraph 5.18) shows how Acrobat could be linked to a simple database, it was necessary to view the information through a browser. This slowed the system to a degree that was felt to be unacceptable to factory users and adversely affected the function of the hyperlinks. Nevertheless the creation of this information system justifies Adobe's claim that their forms plug-in enables read-only Acrobat documents to function as the user-interface to a database. Naturally, the database can be as sophisticated as required by any maintenance organisation as long as it can send and receive data via a web browser.

The Acrobat DC system was not evaluated with users in the TPM environment of the shop floor at Bridgend, but it was demonstrated to managers. For this reason its creation can be seen to lend only partial support to the hypothesis. More research is needed to investigate the extent to which shop floor personnel will enter or retrieve data from a hypermedia information system if the means to do so were provided.

The interviews with maintenance specialists suggest that what is missing from the Acrobat Hybrid system is the ability to input and access the dynamic data present within a CMMS. Examples were given such as:

- Checking the availability of spare parts via a link to the stores database.
- Input of fault descriptions and solutions.
- Recording planned maintenance task completion.
- Querying of a fault history database.

Those interviewed felt that the main benefits of the system were faster access to information that can be expressed in a very usable form and the formation of a repository of maintenance knowledge, which can be updated by the work force. One interviewee suggested that the Acrobat hypermedia system should be expanded to include more information besides that used for maintenance. Examples are quality information, health and safety information and test procedures. This is now being investigated at Cranfield in two separate projects.

The way in which the functions of a conventional CMMS might be delivered using a hypermedia digital manual as a user-interface is shown in Figure 7-1.

7.3 Support for Research Hypothesis

The results of the research support the hypothesis and show the areas where more research is needed.

7.3.1 Usability of hypermedia

The research strongly supports the hypothesis in one important respect. For any information system to be effective, it must be used in preference to other sources of similar information. This research indicates that shop floor personnel would use a hypermedia information system. Usability trials showed that typical users found the pilot system both easy to use and useful, and that they intended to use it in future. Also, their prior use of the system, experience of computers or 'computer anxiety' did not significantly affect users' responses. This result compares very favourably with the low level of CMMS usage by operators found by Swanson (1997) and Boznos (1998).

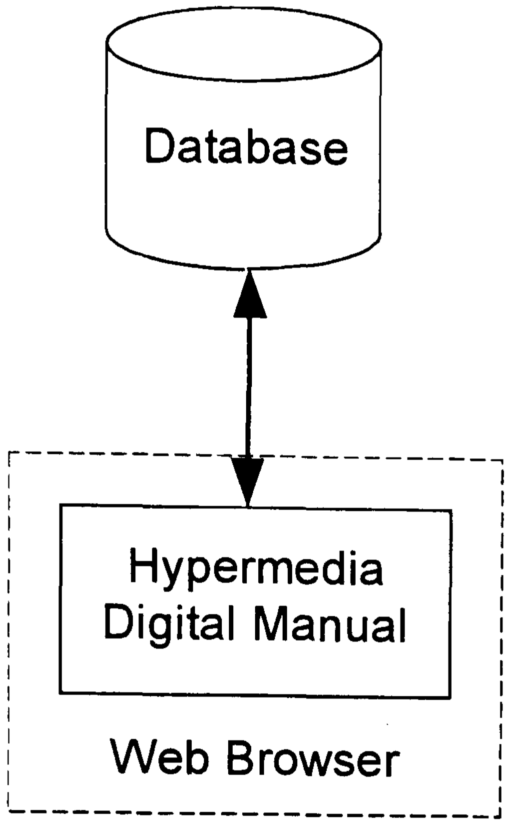


Figure 7-1 Proposed use of a hypermedia manual as a user interface for a CMMS

7.3.2 Costs and benefits of hypermedia

The cost-benefit analysis indicates that a hypermedia information system similar to the pilot system used in the research would probably be cost-effective. However, since the calculation was based on many estimates, a sensitivity analysis was carried out. This showed that the likely benefits varied widely between $27,000 and $1.3 million. Nevertheless the potential benefits are significant and those benefits that were not quantified are also likely to be significant.

Note that the costs of creating the pilot hypermedia system do not indicate the costs of a full-sized system that might be supplied by a process vendor and maintained by the process user. However the fact that Giddings & Lewis are providing hypermedia manuals in PDF format to support their latest machining lines indicates the value of this approach.

The costs of production of hypermedia maintenance manuals will fall in future as digital techniques become more common in the production of paper manuals, and cost-effective hyperlinking strategies become better understood. Open hypermedia systems like Microcosm will enable significant reductions in the cost of authoring hypermedia information systems. Research is needed to investigate how the cost of hyperlink creation and maintenance might be reduced for Acrobat documents.

7.4 Contribution to Knowledge

The research hypothesis is confirmed. A hypermedia maintenance manual has been shown to be an effective means of supporting team-based maintenance. In addition to the benefits of usability and cost-effectiveness, the research suggests that a hypermedia information system need not be inferior to a conventional CMMS. More research is needed to evaluate the effectiveness of hypermedia for the provision and collection of maintenance management data in a TPM environment.

Although the research took place in a teamworking environment, there is no reason why the benefits of hypermedia need be limited to this type of environment. Hypermedia has been shown to facilitate the rapid delivery of information in highly usable form. This feature need not be limited to teamworking or indeed to maintenance information.

Adobe's portable document format has been shown to be a very effective medium for an industrial hypermedia information system. The requirements for robustness and usability in the industrial environment have meant that paper-based information systems still have many advantages over digital ones. The Acrobat user community is dominated by publishers and service sector users. There is no published research on the use of Acrobat Exchange to create a hypermedia information system for factory users. The research described in this thesis shows this to be a practical and effective means of creating such systems.

The literature search revealed several maintenance information systems that have similarities with the one developed here, but there are two features of the system described that are unique, besides the use of PDF. These are the ease with which team workers can update the system, and the use of voice input for fault logging and solution entry. These features support the use of the system in a team environment.

Many of the subjects who took part in the usability trials were unfamiliar with the system, and all were given only five minutes training. There was no significant difference in the usability results between those with prior experience of the system and those without. Furthermore those subjects who needed no prompting, and whose times were recorded in Table 6-3, included people with no prior experience of the system. This suggests that a hypermedia system like the Acrobat One system has no significant training requirement. This is of great value to manufacturing organisations that seek a flexible work force.

Although such a system may be expensive to construct today, it offers significantly more potential for downtime savings than today's CMMS. This is because the hypermedia system described in this thesis represents a 'bottom up' approach which provides information directly to those charged with the execution of maintenance, rather than the 'top down' approach which is common today. In addition to this, the cost of producing such a hypermedia system is continually reducing through developments in computer hardware and software.

7.5 The Use of Acrobat for Industrial Hypermedia Systems

Although Acrobat Exchange is a very simple hypermedia system, it has several important advantages for authors of industrial hypermedia systems:

1. Exchange converts any information that can be printed from a PC to a standard format (PDF). This is as quick and simple as printing.
2. PDF documents can be distributed and viewed over an intranet or the world-wide web.
3. Because of the ease with which PDF documents can be created, users can update a knowledge base by creating documents to be added and accessed via hyperlinks.

4. PDF documents are secure. Acrobat Reader does not allow editing and PDF files can be password protected.
5. PDF documents can accept data input and allow data retrieval through a web browser via the forms plug-in.
6. PDF documents possess all the 'Visual Factory' advantages of paper with the additional advantages of:
   - Greater clarity.
   - Simpler revision control.
   - The ability to find information rapidly using a text search.
   - Intuitive navigation using hyperlinks.
   - The ability to display moving images to enhance communication.
   - No limit on amount of information.

7.5.1 Comparison with open hypermedia systems

Compared to an open hypermedia system like Microcosm, Acrobat has definite limitations. Most serious is the need to create each Acrobat hyperlink explicitly whereas Microcosm has a rich set of different hyperlink types, some of which are created automatically and some by the user. In this way, Microcosm dramatically reduces the time taken to create hypermedia applications. The drawback of the Microcosm approach from the point of view of the factory user is the complexity of the user-interface required to deliver these advanced functions.

Another requirement of an industrial hypermedia system is the ability to view engineering drawings and objects associated with them. On open hypermedia system seems to have advantages here, and an example is the way that Microcosm is able to create automatic hyperlinks to CAD objects. This is only possible if the CAD drawing is recognised by Microcosm, which can be achieved by converting each drawing to a neutral format such as DXF or by providing Microcosm viewers to match all popular CAD systems. The second option is necessary if editing of source documents is to be avoided, but it is unlikely because of the cost and complexity involved. The first option seems possible, however the main problem with neutral file formats such as DXF is that they are supported to different degrees by different CAD systems. If a truly universal drawing format is needed, the only way to ensure document integrity is to convert all drawings to a raster format such as TIFF or PDF. If this is done however, an open hypermedia system like Microcosm cannot create automatic hyperlinks to drawing objects. This means the links to drawing objects must be entered manually which denies authors the opportunity for automatic hyperlink creation.

The other serious limitation of Acrobat, which is overcome by Microcosm, is the inclusion of the Acrobat hyperlinks with the media to which they are anchored. This means that there can be only one set of hyperlinks associated with a set of documents. Although the provision of multiple sets of hyperlinks did not seem beneficial at Ford, there are occasions when this might be useful. Research is needed to investigate the feasibility of an Acrobat plug-in that would allow the creation of multiple sets of hyperlinks related to a set of PDF documents.

7.6 Recommendations

The research described in this thesis illustrates some important issues for the production of digital manuals.

1. Wherever possible, authors should obtain CAD drawings in digital form. This avoids the cost of scanning, improves clarity and reduces file size. To avoid the need to purchase a viewer or a seat of every CAD application used to create a set of drawings, a copy of each drawing should be exported from the original CAD system in a neutral file format. A raster format such as TIFF is preferred since this preserves document integrity. PDF files can then be created from the neutrally formatted drawings.
2. Authors should obtain digital photos to reduce the time and cost of scanning.
3. If a human-centred information system is required, the user community should be encouraged to take their own digital photographs. As well as developing a sense of ownership, this ensures that images are captured that communicate effectively with users.
4. The first version of a digital manual should be constructed during the design process. It is much more cost effective to source the media required at this stage and the preparation of a maintenance manual can be seen as part of the concurrent engineering process.

7.7 Conclusions

The following is a summary of the conclusions of this research:

1. A human-centred information system using hypermedia is an effective means of support for team-based maintenance.
2. The benefits of a hypermedia system are mainly in the ease and speed of access to information.
3. Hypermedia systems can be designed so that little or no training is required
4. Acrobat Exchange from Adobe provides a means by which a robust and effective hypermedia manual can be authored cheaply and simply.
5. Acrobat Exchange provides a means by which system users can update the hypermedia system as process knowledge grows.
6. The production of a hypermedia manual is faster and cheaper if the information for inclusion is available in digital form already.
7. Computer animation and computer-generated images can communicate more effectively than video or photographs in some circumstances. The cost of provision of such media may still be prohibitive, but it is falling. Where such media are available, they should be considered for inclusion in a hypermedia manual.

8. A touch screen is a practical means of navigation for users who dislike the keyboard or mouse, but a touch screen may require larger icons for reliable interaction.
9. Fault descriptions and solutions can be input to a database in the form of speech although this development has not been shown to be robust enough for factory use.
10. A hypermedia manual has been developed which can function as the user-interface to a database. In this way, a hypermedia manual could be expanded to provide the functions of a simple CMMS.

7.8 Future Work

There is much scope for future development of hypermedia information systems based on PDF documents, which might take into account developments in knowledge-based systems, document management systems and user-interface design. The research described in this thesis applies only to the maintenance process, specifically in a TPM environment. The use of hypermedia manuals would benefit any kind of maintenance activity, and the ease with which PDF manuals can be updated means that they become live documents which can be used to reduce costs during the entire life-cycle of a product or process.

Specific areas for future research are described below:

1. The use of Acrobat forms to provide integration with a database could be investigated. This will allow the design of hypermedia maintenance documentation that can be used as the user-interface to a CMMS. A full comparison could then be made between a document based hypermedia information system and a CMMS.
2. Research could be carried out in collaboration with machinery suppliers who would create a full-size hypermedia maintenance manual. Research would evaluate the use of the manual in a factory where it is the only means of access to maintenance information. A usability comparison could be made between different information delivery methods such as a browser, a CD-ROM or paper.
3. The ease with which users can update a full-sized manual could be investigated. The updates would be part of users' continuous improvement activities and the process could be studied in terms of the management of knowledge.
4. Research is needed to investigate the ease with which a PDF manual can be maintained. Digital documentation can provide many users access to one set of documents, which can reduce the cost of revision control. However, the ease with which this can be done on a full-sized system is unknown. The maintenance of the hyperlinks would require particular attention.
5. Research could be carried out to investigate the inclusion of different types of technical information into a hypermedia manual, such as circuit diagrams, PLC ladder logic etc.
6. A plug-in could be developed to overlay the link structure from an external linkbase onto PDF documents.

7. The inclusion of data collected during the design and commissioning of a manufacturing process could be investigated. The concept of a digital manual could be extended to become a fully hyperlinked history of life-cycle of an asset. It may be possible to improve reliability by using hypermedia to close the loop between operators, maintenance personnel and designers.
8. The use of hypermedia to deliver other forms of manufacturing information could be investigated. Research is being carried out between Cranfield University and a mobile phone manufacturer to investigate the provision of hypermedia assembly information. The main benefits are felt to be enhanced communications and a reduction in the cost of revision control.

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Appendix A - The Automotive Industry and Ford

Introduction

This appendix will describe the development of the automotive industry through a brief examination of the history of the Ford Motor Company. This will also explain the reasons for today's emphasis on teamwork and TPM.

This appendix will describe the unique contribution made by the Ford Motor Company to manufacturing in general and automotive manufacturing in particular. As with other industries, companies within the automotive industry are continually borrowing ideas from each other and refining them to suit their own needs. This appendix will show how the Japanese learned from the Ford Production System in the development of just-in-time and total productive maintenance, and how Ford in turn is learning from the Japanese and applying these principles in its own factories.

The role of maintenance in automotive manufacturing is explained, as well as the way in which the need for effective maintenance of automated equipment has affected the workforce in automotive manufacturing.

The First Fords

The following description of the birth of the Ford Motor Company is taken from the second book in a series of case studies in business history entitled 'Individual Enterprise and National Growth' by Hidy and Cawein (1967).

Henry Ford was born in 1863, the son of a Michigan farmer. He was interested in mechanical devices from an early age and at school, he and his friends built a steam turbine which ran at 3000 rpm attached to the school fence before it exploded injuring Ford and one of his friends. He left school at 17 and against the wishes of his father, Henry went to work in Detroit as an apprentice with the Michigan Car Company who made railway carriages. He was dismissed after a week and began a series of short-lived apprenticeships with other firms ending with an engine works of a shipbuilding firm where he completed his apprenticeship. He supplemented his income repairing watches and after completing his apprenticeship he became a travelling mechanic for the Westinghouse Company, repairing steam engines.

After he married, he returned to the farm and started experimenting with petrol engines. He left the farm again and went to work at the Edison Illuminating Company. In 1896, he started building his first engine and some friends helped him complete it and mount it on a primitive car. At that time, others such as Ransom Olds, the Peugeot brothers and Karl Benz were building cars, but these were far too expensive for any but the wealthy to afford. When the Edison Illuminating Company offered Ford promotion on condition that he give up his experiments, he resigned and began working full time on the problem of mass production of the automobile.

In 1899 with the backing of investors, Ford set up the Detroit Automobile Company with himself as superintendent and a small stockholder. In two years, they produced about 20 cars. One of his competitors, Olds made 425 cars in 1901 using such innovations as the assembly line and interchangeable parts. When the Detroit Automobile

Company failed in 1901, Ford launched the Henry Ford Company, which made racing cars. He became world famous in 1903 when his car *999* broke all world records for automobiles. He used his fame to launch the Ford Motor Company in 1903, which was controlled by Ford and his partner Alexander Malcomsen. Malcomsen's clerk James Couzens was brought in to run the business side of the Ford Motor Company and Harold Wills, who like Ford was an ex-apprentice toolmaker from Detroit, was appointed as designer and metallurgist. In 1904 the Ford Motor Company employed Charles Sorensen as head of production. He became an expert in production techniques and was one of the key designers of the Ford production system. He was also a strict disciplinarian and during his 40 years with Ford he rose to become the company's first president.

Ford and Malcomsen argued about company policy. Malcomsen felt that the company should build expensive cars for the wealthy but Ford felt they should develop a light inexpensive car for the masses. Ford gained control of the company by forming another company supplying engines and parts to the Ford Motor Company at high cost. This smaller company reduced the profit of the Ford Motor Company so that dividends fell, causing Malcomsen to sell his shares. Ford bought enough stock to gain overall control of the company and he was now free to develop his car for the masses - the famous Model T.

Highland Park

The Model T was introduced in the autumn of 1908 at a price of $850 for the touring version. In spring of 1909, Ford announced the opening of the first phase of a new factory in the Detroit suburb of Highland Park. This factory was continually expanded as output of the Model T rose and innovations in production engineering meant that the manufacture of previously sub-contracted components was brought in-house. Ford also started to move the assembly operation to a series of branch factories so that output could be increased without further expansion of Highland Park. It was also found to be far cheaper to ship kits of parts across America for final assembly nearer the customer, than to ship finished cars. At Highland Park, there was continuous experimentation to develop new production techniques including the moving assembly line, the development of which is described in the following excerpt from by Charles Sorensen's book 'My Forty Years With Ford' as follows:

> 'As may be imagined, the job of putting the car together was a simpler one than handling the materials that had to be brought to it. Charlie Lewis, the youngest and most aggressive of our assembly foremen, and I tackled the problem. We gradually worked it out by bringing up only what we termed the fast-moving materials. The main bulky parts, like engines and axles, needed a lot of room. To give them that space, we left the smaller, more compact, light-handling material in a storage building on the north west corner of the grounds. Then we arranged with the stock department to bring up at regular hours such divisions of material as we had marked out and packaged.
>
> This simplification of handling cleaned things up materially. But at best, I did not like it. It was then that the idea occurred to me that assembly would be easier, simpler, and faster if we moved the chassis along, beginning at one end of the plant with a frame and adding the axles and the wheels; then moving it past the stockroom, instead of moving the stockroom to the chassis. I had Lewis arrange the materials on the floor so that what was needed at the start of assembly would be at that end of the building and the other parts

would be along the line as we moved the chassis along. We spent every Sunday during July planning this. Then one Sunday morning, after the stock was laid out in this fashion, Lewis and I and a couple of helpers put together the first car, I'm sure, that was ever built on a moving line.

We did this simply by putting the frame on skids, hitching a towrope to the front end and pulling the frame along until axles and wheels were put on. Then we rolled the chassis along in notches to prove what could be done. While demonstrating this moving line, we worked on some of the subassemblies, such as completing a radiator with all its hose fittings so that we could place it very quickly on the chassis. We also did this with the dash and mounted the steering gear and the spark coil' (Sorensen, quoted in Ohno, 1988)

In 1914, the system of pulleys and ropes was replaced by a powered assembly line to move the chassis. The continuous improvements in productivity at Highland Park were matched by cost reduction through the removal of labour hours from the product and by reducing stocks (Williams *et al*, 1992). Between 1910 and 1916, the total labour content of each car fell from over 400 to 130 hours. In 1915 Highland Park had stock cover of 3-5 days for major parts like chassis and engines and in 1913 buffer stocks between departments were down to a few hours.

As well as enabling the Ford Motor Company to out-perform its far less efficient suppliers, the improved manufacturing system allowed Ford to reduce the price of the Model T to $490 dollars in 1911 and $360 in 1916. In 1926, the car still sold for $380 which compared with a salary of around $800 for a school teacher meant that the car was now an affordable commodity. Henry Ford's original aim of producing a car for the masses had been achieved so that in his book 'Today and Tomorrow' he was able to claim that:

"The Model T is low-priced and serviceable - the man who makes it can buy it." (Ford, 1926)

This claim was also due to the Ford Motor Company policy of paying high wages. Building the Model T was hard work. Workers had no union representation and they were expected to co-operate with the labour intensification without protest. The only way they could resist was to resign, which many did. In 1913 the labour turnover was 70% which meant that the company was losing trained and experienced workers too fast. The problem was resolved by Ford, Couzens and John Lee who was head of the Personnel Department. In 1914, they decided to introduce a $5 a day minimum wage which was payable to any worker over the age of 22 and those with dependents who had six months' service. The $5 a day wage was significantly higher than the industry average, although the low labour content of the Model T meant that it was easily affordable, and Ford was widely praised as a great humanitarian. As a result, labour turnover decreased and productivity and morale increased dramatically.

If the concept of mass production originated in the bicycle industry and Ford's competitor Olds had pioneered the assembly line, it was the Ford Motor Company who perfected these techniques at Highland Park and foreshadowed what we now call lean manufacturing (Williams *et al*, 1991).

The River Rouge Plant

In 1915, Henry Ford realised that Highland Park was not going to be able to meet demand for the Model T, and he chose another Detroit suburb on the River Rouge as the location for an ambitious new factory. Construction of the factory, which became known as 'The Rouge' began in 1916 but it was delayed by America's entry into the First World War in 1917. During the war, Ford used some of the capacity at Highland Park to manufacture equipment such as steel helmets and machinery such as the V12 Liberty aero engines for the war effort.

Another delay in the construction of The Rouge was a dispute with minority stock holders, particularly the Dodge brothers who resisted Ford's expansion plans which were financed by cutting special dividends. The Dodges needed these dividends to finance their own car company, and they took Ford to court over the issue. Ford won in court, and he then used the same tactics that he had against Malcomsen to buy the Dodges out of the Ford Motor Company. By 1920 Henry Ford, his wife Clara and his son Edsel jointly owned the whole of the Ford Motor Company.

In 1924, the 150-acre Rouge factory was in operation as a raw material conversion plant. The Rouge was used to turn iron ore, wood, leather, cotton and rubber into components to be assembled at Highland Park and its branch factories. A year later many of the assembly departments of Highland Park were transferred to The Rouge which became the world's first fully integrated car factory. The Rouge represented a major improvement over Highland Park in terms of lead-time reduction. At Highland Park, Sorensen was able to reduce the total time taken to convert raw material to finished products delivered to a dealer from 21 days to 14 days. The vertically integrated nature of The Rouge allowed this conversion to be completed in just 4 days (Shiomi, 1995). It took just 28 hours and 20 minutes to convert raw material to a finished tractor (Ford made farm vehicles as well as cars) within the factory (Hidy and Cawein, 1967). One of the benefits of the speed of conversion was that since the Ford Motor Company bought its materials on 30 days credit and always sold its cars for cash on delivery, it could bank the cash before paying its suppliers (Williams *et al*, 1991)

Fordism

Ford's achievements at Highland Park and The Rouge were published at the time in *The Engineering Magazine* and *Industrial Management* (Shiomi, 1995) and they attracted many visitors from other countries. These included such famous names as André-Gustave Citroën, Louis Renault, Giovanni Agnelli (Fiat), Herbert Austin and William Morris as well as many from companies outside the automotive industry. Ex-patriots from Sweden who had worked in Ford factories also took their knowledge back home. It was not until 1929 that Kiichiro Toyoda (the founder of the Toyota Automobile Company) visited The Rouge and it was in 1950 that his successor at Toyota, Eiji Toyoda led a study tour of the plant before returning to Japan to begin full scale production of passenger cars. These visitors tried to emulate the Ford production system but they did not experience the same success as Ford. This was partly because they did not have the enormous market opportunities and cheap immigrant labour enjoyed by Ford and they seldom understood fully the innovations they witnessed (Williams *et al*, 1991).

The many adaptations of the basic Ford production system have become known as *Fordism* but the stereotypical view of Fordism is believed by some to be a long way from the reality at Highland Park and The Rouge. These factories represented an approach to production management, which was far closer to lean manufacturing than is commonly supposed.

Henry Ford and Lean Manufacturing

At the fiftieth anniversary of the Ford Motor Company, the company claimed that their production system was a product of America's industrial history and had seven elements; power, accuracy, economy, system, continuity, speed and repetition. What is less well known is how many of these features had been developed in the early days. Reference has already been made to the continuous reduction of the labour content of Ford's products, the low levels of inventory and the speed of conversion of raw materials at The Rouge. However, there are many other factors of the early Ford production system that anticipate today's lean manufacturing techniques, and some of these are described below.

Multi-machine manning

One aspect of the continuous reduction of the labour content of the Model T was the use in some areas of one man to operate two machines. In the machine shop, certain single fixture machines were relocated to face each other so that an operator could re-load the first machine whilst the second completed its cycle (Williams *et al*, 1991). In the Toyota production system, this technique is known as a *multi-process operating system* (Ohno, 1988).

Set-up reduction

The benefits of set-up time reduction were recognised at the Highland Park machine shop and several innovative methods were devised as a result. Set-up time was reduced through the use of quick acting clamps and in some cases set-ups were eliminated by using 'multiple tooling' so that several cuts could be taken between set-ups. An example of this was in engine block production where the top and side faces could be machined on the same machine before re-fixturing was necessary. Special fixtures were developed to allow 15-30 engine blocks to be finish machined in a single pass and as many as 104 small parts such as a valve lifter could be ground in a single pass. The Ingersoll milling machine used for front axle bodies was adapted to take two components at a time and to make 24 cuts before re-fixturing. Ohno (1988) contrasts this approach with the Toyota production system, which combines much smaller batch sizes with reduced set-up time.

Although there is evidence of much good production engineering practice to reduce set-ups, they were never a big problem at Highland Park because of the relatively low product variety compared with competitors such as General Motors (Williams *et al*, 1991).

Kaizen

An example of the culture of continuous improvement at Highland Park has already been given in the quotation from Charles Sorensen who describes the Ford Motor Company elsewhere in his book as '... an organisation which was continuously experimenting and improvising to get better production' (Sorensen, 1956). Ford also enlisted the help of his semi-skilled workers to improve his manufacturing processes as Klann describes.

> 'A lot of these ideas came from the men as well as from people in supervisory positions. Lots of them came from the men. You went and asked the men for an idea then tried it out. If it worked, you thanked him for it, or maybe made a foreman out if him' (Klann, quoted in Williams *et al*, 1991).

Klann himself had been taken on as a machinist in 1905 and after moving to the tool room, he was made a roving pace setter in 1907 before being promoted to assistant in charge of motor assembly in 1910. By 1919 he was assistant superintendent (second in charge) of the Highland Park factory (Williams *et al*, 1991)

Williams *et al* make the point that the layout of The Rouge itself constrained the Ford Motor Company in process improvement since the processes were rigidly coupled by conveyors with no inter-process buffers. Since this forced all processes to move at the same pace as well as limiting the scope for layout changes, they argue that the concept of single process improvement was rendered obsolete. In contrast the Volkswagen plant in Wolfsburg emulated The Rouge in many respects except that it de-coupled the individual stages of manufacturing with buffers.

Waste reduction

It is clear from his own writings that Henry Ford appreciated the importance of low stock and the value of time. On page 114 of 'Today and Tomorrow' he writes:

> 'Time waste differs from material waste in that there can be no salvage. The easiest of all wastes, and the hardest to correct, is the waste of time, because wasted time does not litter the floor like wasted material. In our industries, we think of time as human energy. If we buy more material than we need for production, then we are storing human energy - and probably depreciating its value...
>
> ...On the other hand, it is a waste to carry so small a stock of material that an accident will tie up production' (Ford, 1926).

Elsewhere in the book he describes how scrap metal is reclaimed and even worn out drive belts and hand tools are refurbished and reused. Ford makes the interesting point that he regards wasted material as wasted labour. This is the reason that he is keen to avoid waste in the first place, but then to minimise its cost by reclaiming what he can. It is not clear whether his accountants took the same view.

Ford devotes the whole of chapter 11 to the efforts of the Ford Motor Company to save timber. These efforts included collecting all the brush wood, reusing the wood from packing crates, forestry management, the use of combined heat and power systems and conversion of scrap wood into paper, board, charcoal and chemicals.

Plant layout and flow production

According to Shiomi (1995), there were 50 miles of belt conveyors at Highland park, but Williams *et al* (1991) record a lower figure of 27 miles at The Rouge in the 1920s and much less at Highland Park. Whatever the figures, the pioneering and extensive use of conveyors became a well known feature of the early Ford factories so that observers at The Rouge likened it to a 'great water supply system' with mains and many feeder pipes (Shiomi,1995).

Even where conveyors were not used, Ford either used other material handing devices such as cranes, chain driven lines and overhead monorails or simply arranged manufacturing processes so that work-in-progress travelled shorter distances. At Highland Park, machines and processes were placed close together and in their sequences of use so that in many cases they could be connected by simple devices like gravity slides and roller beds.

It is clear that Henry Ford appreciated the benefits of flow production and that many of the material flow techniques developed at Highland Park for the manufacture of components and sub-assemblies could equally be applied outside the motor industry. This is the claim made by Womack and Jones (1996) who exhort their readers to consider their operations as a value stream which must be made to flow more smoothly.

Standardisation

Henry Ford was a great believer in standardisation. In chapter 7 of 'Today and Tomorrow' he describes how the Ford Motor Company used standards in its products, its processes and its documentation. He draws a distinction between standardisation that marks inertia and standardisation that marks progress. He clearly believes in the latter when he says:

> "standardization means nothing unless it means standardizing upward" (Ford, 1926).

When considering design and manufacturing decisions, he distinguishes between standards that are externally imposed on a manufacturing unit and those that are generated inside the unit. Again he prefers the latter since externally imposed standards tend to dull human ingenuity instead of sharpening it.

Nevertheless, Ford recognises the need for some external standards such as those regulating the quality of raw materials and in metrology for example. Accurate measurement systems were fundamental to Ford's use of interchangeable part in his cars and processes. He describes how the Ford Motor Company bought the US manufacturing rights to Johansson precision gauge blocks and even employed Mr Johansson at Ford.

Ford refers to the series of books of 'Ford Tool Standards' that describe all the details of the Ford system of standardised machine tool parts. The gears, keys, shafts, levers, pedals and other elements of Ford's machine tools were all standardised so that in some cases only special castings were needed to produce even quite specialised machinery. Ford cites several advantages of this approach such as:

- Reduced training cost
- The reapplication of production experience gained in Detroit to another Ford plant in Barcelona, Oklahoma or São Paulo.
- Cheaper machinery.
- The ability to salvage spare parts from faulty machinery for re-use elsewhere.
- Simpler and easier maintenance and repair.

Elsewhere in the book, Ford quotes detailed cost savings that have derived from his continuous improvements but although he mentions the advantages of documentation of standard parts for maintenance, he does not quantify the benefits.

The 5Ss and TPM

Ford was passionate about cleanliness. In 'Today and Tomorrow' (Ford, 1926) he describes the quarrying of stone for making glass for Ford cars. He claims that the quarry and crushing plant are clean and that there is an absolute rule that every operation must be cleanly performed with any dust being extracted and removed. The reasons for this are both for the health and safety of the men and out of concern for the local environment around the quarry.

Ford describes how the company bought the Imperial Mine for iron ore extraction and immediately started to clean it up since "that is always the first thing to do in order to find out what you are about". This approach to cleanliness is strikingly similar to the 5Ss advocated by Japanese writers such as Nakajima (1988).

Later in the book, he describes the 'Ford principles of management' as he applied them to the Detroit, Toledo & Ironton Railroad, which had been acquired by Ford:

1. Do the job in the most direct fashion without bothering with red tape or any of the ordinary divisions of authority.
2. Pay every man well - not less than six dollars a day - and see that he is employed all the time through forty-eight hours a week and no longer.
3. Put all machinery in the best possible condition, keep it that way, and insist upon absolute cleanliness everywhere that a man may learn to respect his tools, his surroundings, and himself (Ford, 1926).

Taylorism and teamwork

It is often assumed that the early Ford factories were textbook examples of scientific management as described by F.W. Taylor (or *Taylorism*) but Williams *et al* (1991) give many examples which show that this is a misunderstanding of the Ford system. We have already seen how it was possible for workers to suggest ideas for improvement and to be promoted as a result, but it was also true that due to the continual improvements, workers had to be completely flexible as the production process was re-organised. In the search for greater efficiency, Ford believed in the division of labour for assembly operations which were largely manual, although the machines were placed very close together to reduce transport time and ease material handling.

In the machine shops however, processes were often combined in order to reduce set-up time. Although a careful scientific approach was taken to the continuous improvements at Highland Park, performance was not compared against time since Ford preferred to use men known as 'pace setters' to drive the workforce. These men could do every job on the line and their function was both to show the workers how to work faster and to drive them into doing so. To do this, every pace setter had to learn the German, Polish, Italian for "hurry up" (Williams *et al*, 1991).

There is little evidence of teamworking in early Ford factories and this may be partly due to the use of immigrant labour and the consequent language difficulties, but gangs of men performed some assembly tasks. Ford himself seemed to believe in a flexible workforce even if they were not highly trained since he writes:

> "No man in our employment considers himself as fixed in any particular line of work; he is ready, whenever the need arises, to take on some sort of work he may never have heard of before ....
>
> .... Every man is better for having several strings to his bow" (Ford, 1926).

Later in the book, he talks disparagingly of the craft tradition and the existence of unions in English automotive manufacturing since he believes that English workers are held strictly to their crafts.

Ford did not apply his principles of standardisation to wages, since although there was eventually a minimum wage of $6 a day, there were no wage scales and he paid "according to the man" (Ford, 1926). It is not clear whether this was linked to an individual's output as in piecework, but it is difficult to see how this could be achieved in a tightly integrated factory like The Rouge.

Historians have questioned the influence of Taylor on Ford and in any case, according to Helfgott (1987) they were interested in different things. Taylor sought to improve the efficiency of workers through timed studies of their work, and he advocated the separation of work planning and execution. The former should be the preserve of management who would break the work down into a set of specialised tasks each of which required as little thought as possible. Ford, on the other hand, was concerned with technology and would remove direct labour from the production process where possible and was quite prepared, as we have seen, to use workers ideas to improve processes. One of the features of Taylorism that is often criticised is the way in which the division of labour produced repetitive and monotonous jobs. Ford accepted this as a necessity if one was to achieve the low costs and high output that would give the workers a high standard of living. In any case, he reasoned

> "... many men want to earn a living without thinking, and for these men a task which demands no brains is a boon" (Ford, 1926).

Mechanised production replaces hand work

Although the term *automation* was not coined until much later (see below), Ford pioneered the use of many forms of mechanised production for automotive manufacture. Even in the 1920s, this trend was feared by some who said it would destroy craftsmanship, but Ford felt that exactly the reverse had come about (Ford, 1926). He argued that they now needed <u>more</u> craftsmen in the form of expert machinists, toolmakers and machine repairers. He predicted that as Ford Motor Company increased its fund of mechanical knowledge, its production machinery would require less attention from operators, and the shift would be towards the manufacture of production machinery.

Ford saw two of the advantages of machinery over "hand work" as being accuracy and repeatability (p141) and he felt that it was the job of management to ensure that a machine completed its processes with no requirement for hand work.

Between the Wars

The years between 1920 and the end of the Second World War were difficult ones for the Ford Motor Company (Hidy and Cawein, 1967). During the 1920s, many valuable staff from the early days had either left of been fired after quarrels with Henry Ford who was becoming more autocratic. Harry Bennett whose 'Service Department' was made up of guards and labour spies was becoming more powerful and he and Sorensen used fear of unemployment to drive the workforce harder. After much development and many revisions, the Model T had come to the end of its long life and was being replaced by the Model A, but Ford was experiencing serious competition from General Motors (GM).

During the depression years, sales of the Model A fell and wages dropped as a result. There were long and bitter struggles between the workforce and management during which Harry Bennett's men clashed violently with Union organisers. In 1941 after more clashes, Henry Ford finally agreed to Union recognition by which time Ford sales represented 20% of the market for automobiles. During the Second World War Ford factories were used to supply aircraft and equipment for the war effort (for both the USA and her allies, and in Italy and Germany, the fascists) and in 1943 Ford's son Edsel died of cancer. The boardroom struggles at Ford and poor production figures worried the US government who considered nationalising the company, but as an alternative Edsel's eldest son Henry Ford II was released from the Navy to return to the firm. By this time, Harry Bennett and Charles Sorensen had quarrelled and in 1944 Henry Ford the elder asked Sorensen to resign. This was too much for Clara Ford and Edsel's widow who threatened to sell their shares if Henry II was not made president. Henry senior gave in and his grandson became president in 1945.

Ford and Automation

Henry Ford II fired Harry Bennett and began the task of rebuilding the Ford Motor Company. He hired many men from General Motors and associated companies and reorganised Ford along the divisional lines of GM (Hounshell, 1995). In 1947 Ford appointed Delmar Harder as vice president of manufacturing. Harder had been president of press manufacturers Bliss and before that, he had worked for many automobile companies including GM. He claimed to have coined the term *automation* whilst he was at Fisher Body Company - a GM subsidiary. Harder defined automation as "the automatic handling of parts between progressive production processes" and in 1947 he created the Automation Department at Ford (Harder, 1954). Ford's first examples of automation were installed at the Buffalo Stamping Plant where they loaded and unloaded material from the stamping presses and transported it between operations.

Transfer machines

The Ford Motor Company was not alone in developing automated processes. The machines at Buffalo were inspired by work done at GM who produced many of Ford's early automatic machines and had themselves started using automation in the 1930s as a response to a militant workforce. GM had also installed examples of a new type of automated machine called a *transfer machine*.

Principle of operation

A transfer machine is a group of single or multi-spindle machine tools arranged in a linear or radial fashion around an automatic material handling device so that material is processed in a set of sequential steps with no human intervention. Each machine tool processes material until they have all finished their cycles when the handling device indexes all material to the next process. Each process must have a similar cycle time since the slowest process dictates the speed of the machine, and any processes which are significantly faster must wait (i.e. waste time) until the other processes have ended their cycles. It is important that each process be reliable and well supplied with cutting tools since a stoppage on any one process will stop the entire machine (De Garmo *et al*, 1988).

Early transfer machines

Hounshell (1995) records that the transfer machines were first developed and used by Duane H. Church of the Waltham Watch Company. Ford and GM experimented with them in the 1930s but it was a British company, Morris Engines Ltd. who did the earliest large scale development of transfer machines for automotive manufacture. Between 1923 and 1925, Morris Engines developed transfer machines for machining engine blocks, flywheels and gearbox casings but they proved only a partial success since they were over complicated and the technologies required had not been sufficiently developed at that time. These early machines were broken up and their machine tools used separately (Woollard, 1954). In 1932, engineers at Ford Motor Company built a two-station transfer machine and in 1936 they used a seven-station machine from Baird to manufacture drive train components.

Ford's new engine plans

When Harder arrived at Ford, he ordered the rearrangement of the Motor Building at The Rouge and he installed many new machine tools including transfer machines although he regarded the plant as basically obsolete. When Ford senior management asked the manufacturing engineering department to design the "most modern, efficient plant in the country" to make engines (Hounshell, 1995), they suggested two alternative plans. The first plan featured conventional machine tools and material handling systems, but the second featured automated devices designed by Harder's Automation Department (figure 2-1) to load and unload machines as well as automatically inspect, gauge and weigh engine components. After much deliberation and consideration of alternatives, Ford executives decided to demolish the Motor Building at The Rouge, relocate its machinery to the Parts and Accessories Building, and start construction of a new 200 acre site at Cleveland.

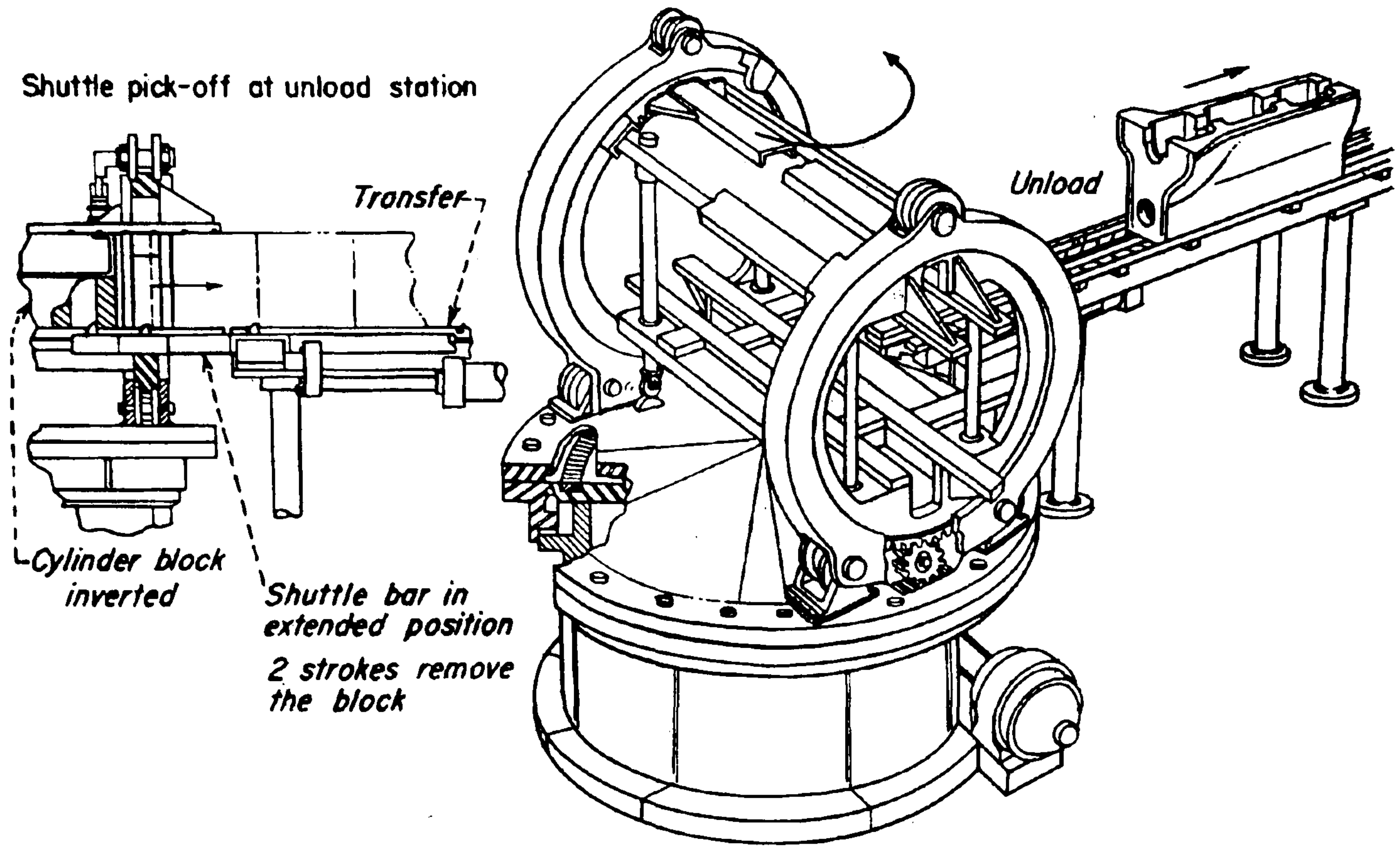

Figure A1 Combined turntable and roll-over mechanism (source: Woollard, 1954)

Automation at the Cleveland Engine Plant

When it opened in 1952, the Cleveland Engine Plant was hailed as a revolutionary development in manufacturing. Hounshell (1995) records the descriptions of the new plant by Ray Sullivan (Harder's assistant at Ford) who claimed that the plant amounted "almost to an industrial revolution" and Ernest Breech (number two to Henry Ford II) who described automation as "an entirely new concept of production". Even Peter Drucker saw automation in revolutionary terms, describing it in 1955 as "a major technological change, a change as great as Henry Ford ushered in with the first mass production plant fifty years ago" (Hounshell, 1995).

Harder himself described the technical details of the plant in an article in the first edition of the journal Automation (Harder, 1954) where he extends his original definition of the term *automation* from automatic material handling to include the effects of automatic handling on every phase of the manufacturing process. His article discusses automation under the headings of:

1. Transfer machine tools
2. Automation (old definition)
3. Control of the automated system
4. Preventive maintenance and
5. The effects on labour and management

In the section on automation, Harder describes the application of automation beyond machining into assembly, repair and testing operations where automated devices must work alongside human operators. He describes how automation principles used to be applied within Ford by the "cut-and-try method" but now they are applied more systematically. He also explains how the demand for new products has made it possible for Ford to invest in completely new plants which simplifies the introduction of automation, as well as allowing designers to design products to suit automated manufacturing processes - design for automation. He refers to the fears of many at the time who felt that the application of automation between transfer machines (i.e. transfer lines) would expose the plant to unreliability which would offset the advantages of automation. However, he argues that if the same maintenance principles that were applied to transfer machines were also applied to transfer lines, then the linking of transfer machines by automation would further benefit Ford by completing the process of automation.

Harder lists the benefits of automation as:

1. Lower production costs through increased output and reduced direct labour (although he accepts the need for more indirect labour in maintenance).
2. Increased machine speed where this used to be limited by material handling constraints.
3. Improved quality as there is now less chance of parts hitting each other or falling to the floor, and the automated lines now include automatic gauging.
4. Improved safety since many accidents used to occur during manual handling of cumbersome components such as sheet metal pressings.

Maintenance at the Cleveland Engine Plant

In his discussion of control systems (which were hard-wired relay systems), Harder (1954) refers to the layout of the electrical control cabinet where the relays and harnesses are exposed for easy maintenance. He also describes the cutting tool control system that is designed to reduce the chance of tool breakage. The tool control board includes a device called a *toolometer dial* that times the usage of groups of cutting tools and suggests when replacement is necessary. Transfer machines are particularly vulnerable to minor stoppages such as tool breakage since one broken drill in a 24 station machine would stop the whole machine. When a transfer machine is shut down for tool change, all tools that are approaching the end of their life are also changed to minimise downtime.

Harder devotes a section of his paper to preventive maintenance, which he believes all manufacturers should utilise, but which is particularly important in an automated factory. This is because such a factory is geared to produce a particular number of units per hour, and lost units cannot be made up without expensive extra shifts. Under preventive maintenance, Harder lists activities such as:

- Keeping adequate records of machinery and equipment reports.
- Scheduled lubrication.
- Constant checking.

He states that "The purpose of preventive maintenance program is to statistically determine the anticipated life of perishable parts of our mechanical equipment and to see that those parts are replaced before a complete breakdown occurs".

He describes how standardisation has assisted maintenance through agreed codes of identification for hydraulic, pneumatic and electrical systems and design for accessibility of machines. He concludes the section on preventive maintenance by stating that extended use of automation principles has made preventive maintenance mandatory in a well-managed plant.

Although in Harder's time, each Ford plant operated a maintenance department that was distinct from the production function, he describes one effect of automation on the workforce as requiring greater skills. In his view, production processes have become more complex through removal of the need for manual material handling, so production workers should be "selected on the basis of ability to recognize troubles that are threatening. It is apparent, therefore, that our production people must be more highly trained on the average than in the past".

He describes how Ford managers have had to prepare workers to work in automated factories and that the worker, in turn, benefits through a less monotonous job.

Downtime at the Cleveland Engine Plant

Despite the best efforts of Harder, downtime was a problem at the Cleveland engine plant. In a significant study of early automation, James Bright (1958) describes how "Everything had to work or nothing worked" and that the timing and/or elimination of downtime became a critical part of the success of the Cleveland Engine Plant. In the case of assembly operations, Ford used power and free conveyors so that work could queue at a process that had failed without stopping other processes (unless the queue reached capacity) and then carry on when the process had been repaired. This was an implicit recognition of the problems of downtime in a highly complex and integrated factory.

Hounshell (1995) implies that power and free conveyors were not used in the machining lines and although photographs of the plant show stocks of engines in the automation between processes, these conveyors appear to be full. It seems that there was an inflexible connection between machining processes such that a part could not exit any machine if any machine in the same transfer line could not accept a new part.

Perhaps because of the downtime problems, cost studies of the Cleveland Engine Plant showed that unit costs were higher than planned due to higher overheads and higher labour costs although it was accepted that in an automated plant, direct labour now offered limited opportunities for major cost reductions. The other major problem with 'Detroit automation' was inflexibility. In the mid-1950s, US car manufacturers were engaged in a horsepower war as each introduced still more powerful cars. In 1967 Ford's Lima Engine Plant had produced three different six cylinder engines and two different V-8 engines within a decade; but had done so by ripping up old lines and installing new ones. The problem of machine tool obsolescence was recognised and Ford attempted to solve this problem by forcing their suppliers to build machine tools in modules - so called *unitized automation*.

Innovations in maintenance at the Cleveland Engine Plant

Not only was the manufacturing technology at Cleveland highly innovative, the expected maintenance problems resulted in some significant changes in operating procedures. Bright (1958) records how much of the labour that had been displaced by automation was replaced in the form of maintenance labour. However, he feels that is important to distinguish between the cost of maintenance tasks such as installation, commissioning and experimental work, and the cost of downtime. Such cost breakdowns were not available at first, but Ford developed an innovative cost control system for maintenance that allowed managers to pinpoint maintenance problems according to their severity and target their improvement efforts accordingly. This early maintenance management system used tally cards that were filled in by maintenance men and the data transferred to punched cards by clerks. The system used an elaborate set of codes to classify faults by machine, type of repair (9 basic types) and reason for failure. In 1956, there were approximately 175 reasons and each maintenance man had a booklet of codes. The cost control supervisor described some of the drawbacks of the system in terms of the time spent on paperwork and the cost of analysis.

Another innovation was the development and adoption of standards to reduce the variety of spare parts and for identification of wiring, hydraulic, lubrication and pneumatic lines. Quick release fittings were used and accessibility to serviceable machine components was improved. Wiring diagrams and stock lists were made visible at each control panel.

The tool control board with its *toolometer* dial has already been mentioned above, and this innovation was widely copied.

The maintenance force was decentralised by dividing the plant into five 'productive maintenance' areas in order to reduce response time and to allow workers to become more familiar with the maintenance requirements of a smaller number of machines . Each area was given an area maintenance foreman each of whom who had a foreman on each shift. In each area, the maintenance workers were made responsible to the production supervisor for that area.

Procedures were developed for identifying problems, calling for maintenance support and escalating a problem if necessary. A formal request for assistance from central maintenance was only made if the area maintenance workers could not rectify a fault. Lubrication and preventive maintenance were carried out according to a schedule.

Design of automated plant for maintenance

In a later edition of *Automation*, R.N. Johnson of the W.F. & John Barnes Company who supplied the Ford Motor Company with machine tools writes about electrical maintenance (Johnson, 1954). The difference between automated machine tools and older designs was the use of hydraulic, pneumatic and electrical systems as well as the older mechanical devices. Johnson argues that this places maintenance personnel in a dominant position in the production plant, yet machine tool designers have generally focused on ease of operation and output with maintenance being secondary. Unless machine designers give maintenance a higher priority, unskilled and semi-skilled workers who have been displaced by automation would have to be replaced by equal numbers of highly trained service technicians. Part of his solution to this problem is to make designers aware of maintenance by including servicing in customer plants as part of their training and involving them in the construction of the machine tools at Barnes.

Of particular interest considering the subject of this thesis, is the emphasis Johnson places on usable information. He argues that more information should be made available to the customer's maintenance personnel and that it should be in their hands instead of a file in the office. He actually admits that Barnes recommend their customers to encourage maintenance and operating personnel to steal control drawings from their machines since this is a healthy sign of interest in machine operation. He describes how Barnes makes its customer's maintenance personnel familiar with machine operation through:

1. Personal interviews between Barnes engineers and customer production and maintenance engineers before and during design and after installation of a machine.
2. Introduction of mechanical trouble finders on machinery to help maintenance personnel to diagnose problems quickly.
3. Use of customer's maintenance personnel in installation of machines.
4. Presentation of complete information on the controls of the machine which consists of:
    - Schematic line drawings.
    - Machine equipment layouts.
    - Complete equipment parts lists and recommended maintenance stock list.
    - Step-by-step description both in simple graphic form and in writing of the mechanical sequence of operations of the machine.
    - Step-by-step description in written form of the electrical sequence of machine operation.
    - Inclusion of all this into a standard binding.

Automation slows down

When Eiji Toyoda returned from his 1950 study tour of The Rouge, he stated:

> "The scale is certainly impressive, but once I got used to (their) system, I found some faults in it. There is not a great difference (between Ford and Toyota) in terms of manufacturing technology and production methods. In fact, Toyota, with methods like just-in-time, may be ahead. If we modernize our factories and invest in the newest equipment, we should be able to surpass Ford" (Nonaka and Takeuchi, 1995).

Whereas Ford and GM employed ever more complex technology to automate their factories, during the 1950s Toyota developed a new concept of *autonomation* which they described as 'automation with a human touch' (Ohno, 1988). According to Ohno, autonomation means transferring human intelligence to the machine and he credits Sakichi Toyoda (whose son Kiichiro Toyoda founded the Toyota Automobile Company) with the idea. Sakichi developed an automatic loom that stopped instantly if one of the warp or weft threads broke. Automatic stopping devices ensure that poor quality product is not made and that the machine can be left unattended safe in the knowledge that it will stop if there are any problems. This technique also acts as a powerful incentive to ensure that stoppages are kept to a minimum. At Toyota, the principle of autonomation is extended to manual assembly lines where operators are expected to push a button to stop the line if an defect occurs. Ohno describes autonomation and just-in-time as the two pillars of the Toyota production system and they contrast sharply with the relatively inflexible and rigidly paced automated systems at Ford and GM in the 1970s.

According to Ohno (1988) the 1973 oil crisis signalled the end of American style mass production and the beginning of interest in the production system that Toyota had been developing since the end of the second world war. The Toyota production system was designed from the outset to enable Toyota to catch up with the American car manufacturers by eliminating waste. During the 1980s it became obvious to Western observers that the Japanese were succeeding as they took sales from Western car makers. The response of GM was to invest heavily in advanced flexible automation and at the same time to negotiate a joint venture with Toyota called New United Motors Manufacturing Incorporated (NUMMI) by which they hoped to learn the secrets of Japanese success (Rehder, 1994). However GM's market share fell from 48% to 36% in this decade and a comparison in 1989 between GM and Ford concluded that automation was not a factor in the significantly greater productivity of Ford (Harrison and Storey, 1996).

Hoerr *et al* (1998) refer to a slow down in sales of industrial robots in the late 1980s and the problems experienced by GM in integrating its new manufacturing technology with its business systems. They also refer to the vulnerability to downtime of tightly integrated manufacturing systems and the emphasis that this puts on the diagnostic skills of the workforce. Describing the then new GM front axle plant in Saginaw, which was intended to be run entirely unmanned for part of the day, they point out that the workers in this factory were carefully selected and highly trained in electronic, mechanical and problem solving skills. Training was given for over a year before starting work in the plant.

A study by Meredith (1987) found that contrary to the belief that flexible manufacturing systems (FMS) would enjoy extended lifetimes since they could be re-configured as product designs changed, they were found to require constantly increasing maintenance as they wore out and their software accumulated bugs over the years.

A 1996 report from the Brite Euram Future Working Structures project (Future Working Structures, 1996) found a tendency in the European car industry to install short cycle lines with low levels of automation, and in some cases systems with no fixed cycle time due to increasing numbers of variants. The study also found a dramatic reduction in buffer sizes since the end of the 1980s and predicts that this tendency will continue although buffers will not disappear altogether. This seems to imply a link between lean manufacturing and a slow down in automation.

Automotive manufacturing and the workforce

The competition from Japan and subsequent incorporation of Japanese working practices in Western manufacturing has led many writers to consider the effects of 'Japanisation' on Western auto makers (Wilkinson and Oliver, 1990). The success of the Toyota in developing a flexible low cost production system which is responsive to markets has been recognised in the West, and just as industrialists visited The Rouge to learn from the Ford Motor Company in the 1920s, so they started to visit Japan on study tours.

We have seen how the early Ford production system was the inspiration for much of the Toyota production system, but the two key differences are the use of just-in-time (particularly the 'pull' method of production control) and autonomation. Japanese production techniques have affected maintenance in many ways, but in the next sections we will look briefly at skills, standardisation and use of teams.

Skills and deskilling.

Industrial sociologists have argued about whether new technology such as automated machine tools lead to deskilling or 'upskilling' of the workforce (Hendry, 1990). On the one hand are neo-Marxists such as Braverman (1974) who view automation as a capitalist project to appropriate the labour process through rationalisation and mechanisation, which deskills and alienates the workers. On the other hand are those such as Senker and Beesley (1986) who argue that while automation may reduce the number of employees in a factory, it increased the skill content of those jobs that remain and requires extensive training in diagnostic techniques to deliver the promised benefits. The skills required for maintenance tasks are at the heart of this debate and both Braverman and Senker and Beesley considered maintenance in their studies.

Bright's 1958 study of automation described the effect of automation upon skills in some detail. He developed a 17-point scale of mechanisation that is used to investigate the relationship between skill requirements and level of mechanisation. His study covered 13 automated plants including Ford's Cleveland Engine Plant where the most highly automated processes were considered to be mechanised to level 10. Bright felt that skill requirements for operators followed a curve with a maximum at level 4 (figure 2-2) so that direct labour skill requirements are generally reduced of unchanged by automation.

Minor exceptions to this might be an increase in job scope and responsibility through automation. Indirect tasks were similarly deskilled, with the exception of CNC machine set-ups, machine design and construction (where Bright felt that skills up to PhD level were required), and some classes of maintenance work. In the case of maintenance, the greatest increases in skill requirements were in electrical and electronic maintenance. He also refers to a critical shortage of multi-skilled maintenance workers who can diagnose trouble arising from a combination of technologies.

Braverman (1974) points out that Bright's study of automation found that the number of maintenance people needing new electronic skills was very limited and considering the advances in electronics by the 1970s, he further expects the use of automatic diagnostics to reduce the skills needed for maintenance. Braverman also fees that the trend towards modular design, which reduces downtime by allowing the replacement of entire assemblies, contributed to the deskilling of maintenance. Senker and Beesley (1986) feel however, that whilst Bright's analysis may have been reasonable in the 1950s, it was becoming dated by the 1970s. They refer to their own research in 1980 which agreed with many other studies that whilst automated diagnostics may have deskilled a few maintenance tasks, these tasks formed a small part of the job of a maintenance craftsman. Furthermore there was, in general, an increasing requirement for skills and knowledge across a number of trades as well as the ability to systematically diagnose faults and understand the relationship between machine engineering and manufacturing processes.

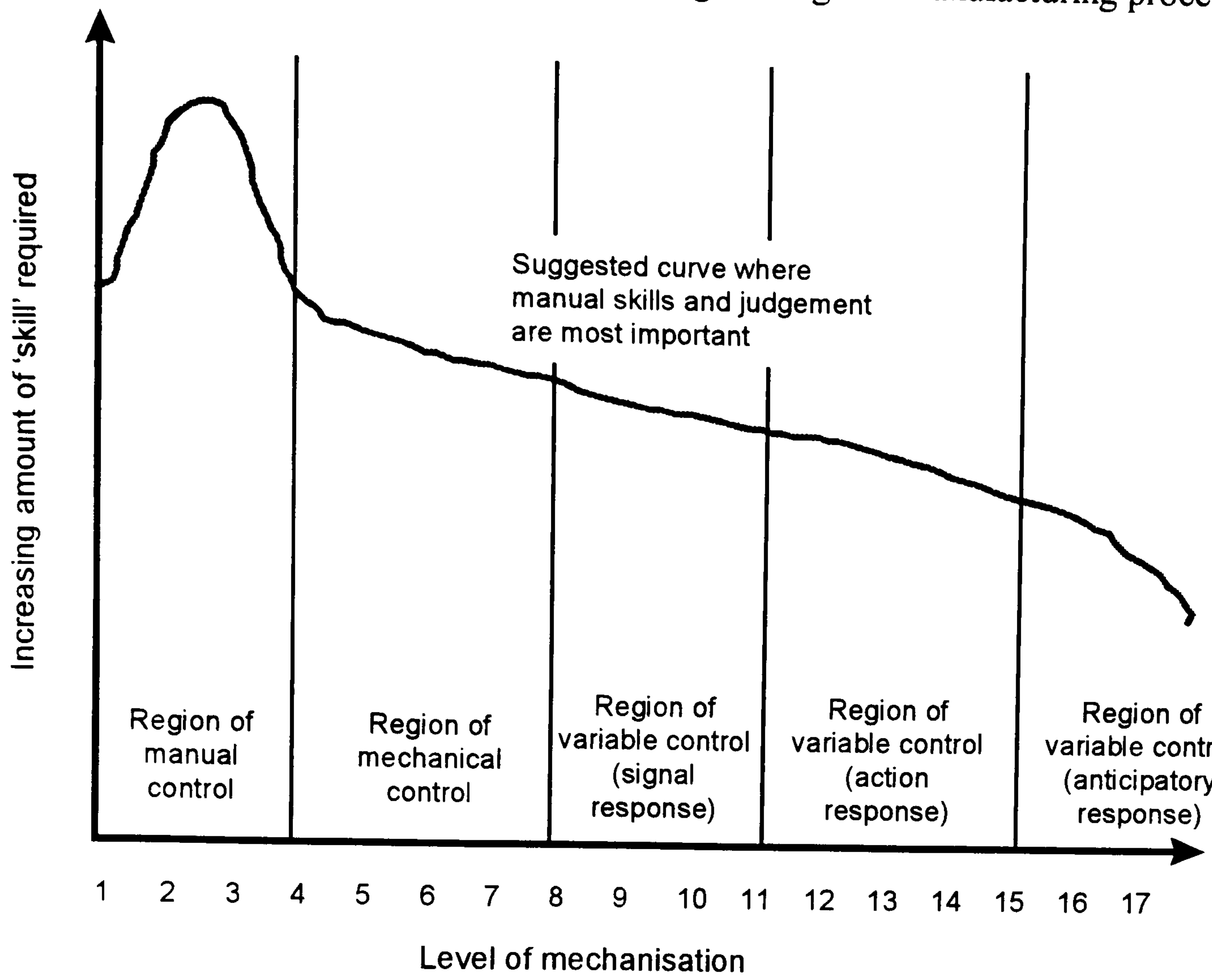

Figure A2 Suggested variation of skill requirements with level of mechanisation (after Bright, 1954)

Hendry (1990) goes further when he argues that the requirement for continuous operation of FMS and the reduction of indirect costs meant that operators now required more detailed technical training so that they could carry out basic fault finding as well as machine setting and CNC program editing. He argues that the debate about deskilling is missing the point that direct production tasks are not the only measure of skill or control over the work process. Research should concentrate instead on intersecting roles and labour markets, internal and external to the firm, not with a single focal skill group. Braverman himself points out that skilled workers and skilled work are not necessarily the same thing which might also imply that the situation is much more complex than a simple debate between deskilling or upskilling theses.

Hendry (1990) describes the changes in skill requirements for maintenance at an automotive manufacturer. Here there was little conflict between production and maintenance staff as the former assumed responsibility for planned maintenance at weekends and some first line unplanned maintenance tasks. At the same time, the skills of works maintenance staff were considerable enhanced to cope with more sophisticated plant and with the development of multi-skilling. In fact maintenance staff encouraged the operators to carry out basic fault finding and repairs as long as they were interested in doing so since it relieved them of some tasks which they considered chores.

Even Shaiken (1989), who argues that CNC technology deskills workers, points to a dichotomy between managers intentions when they introduce FMS and the actual outcome which is high levels of downtime, mitigated to an extent by high output when the systems work. He found that at both plants he studied, automation had resulted in maintenance jobs becoming more challenging.

Skills in assembly operations

The deskilling debate described above has mainly concentrated on machining operations where operators are free to observe the process and carry out indirect tasks such as maintenance, set-ups and inspection. The scope for development of skills in assembly workers is somewhat more limited, especially in the automotive industry where the moving assembly line has become common. Assembly line workers have much less autonomy both physically (since they must remain 'line tied' during production) and intellectually since their jobs are usually specialised and standardised. The degree of autonomy in automotive assembly work can vary significantly from the traditional Fordist assembly line to the Swedish model of assembly cells with the Japanese approach somewhere between these two extremes (van der Meer and Gudim, 1996). In the Swedish approach, the assembly line is broken up into individual cells separated by buffer stock which allows each group more autonomy to work at its own pace. Each group of assembly workers plans and organises its own work, which includes indirect tasks such as routine maintenance. Compared to the Fordist approach, economies of specialisation are sacrificed to achieve greater horizontal co-ordination of activities, which should improve flexibility.

In the Japanese model of assembly, direct production tasks are at least as specialised and standardised as in Fordism, but the operators' jobs themselves are less specialised. Operators are formed into assembly line teams whose responsibilities include indirect activities such as quality control, routine maintenance and improvement activities (van der Meer and Gudim, 1996). In their study of a Scottish clothing manufacturer which had changed from conventional sewing lines to group working cells, they mention workers carrying out quality control activities and some improvement activities but no maintenance tasks at all.

Standards, Taylorism and Mediated Taylorism

We have already seen how maintenance costs can be reduced by standardisation of colour codes for wiring and services, fittings and connectors and by rationalising spare part inventories, but standards can also be applied to maintenance activities. Braverman (1974) describes an approach to maintenance task standardisation called Universal Maintenance Standards (UMS) and he refers to a national organisation which by 1960 had applied work study techniques to establish 52,000 universal elements of maintenance work. These work standards were stored in a central computer that could be used to allow a foreman anywhere in the country to get a standard time for any maintenance task.

Braverman's example is an early case of Taylorism being applied to maintenance and a similar approach is taken in many Japanese factories, the essential difference being the involvement of the workforce. Many writers have commented on the differences and similarities between classical Fordism and Japanese inspired Just-In-Time since both approaches follow Taylor in separating task design and task execution but in the former, task design is the job of management. In the latter task design is carried out with worker input which gives consensus. Conti and Warner (1994) use the term 'Mediated Taylorism' to describe the use of teams of shop floor workers to design job standards, which are continuously improved. They argue that the cycle of job design in Mediated Taylorism is a significant departure from Fordism and illustrate this cycle as in figure 2-3.

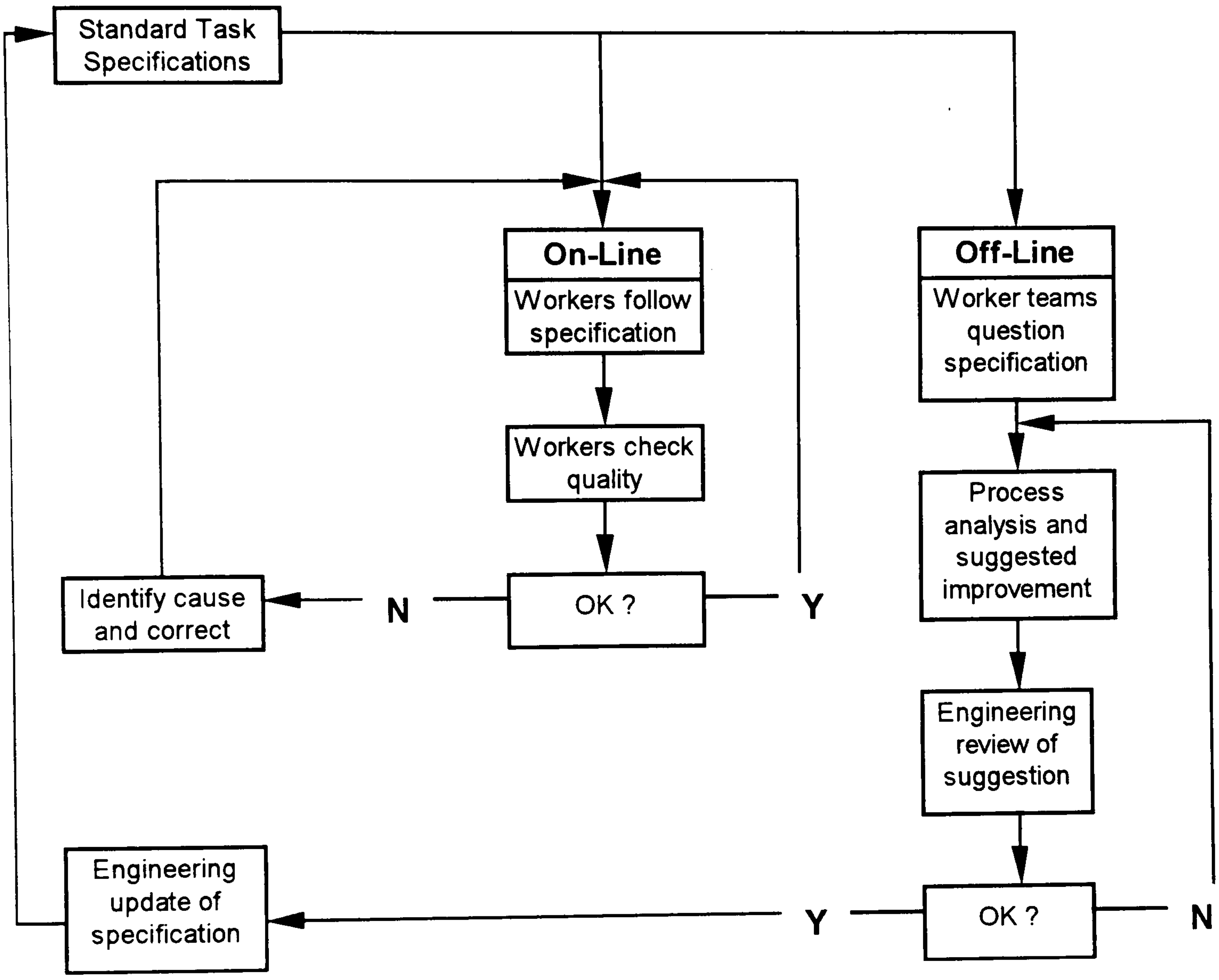

Figure A3 Mediated Taylorism job design cycle (source: Conti and Warner, 1994)

As well as their joint venture with Toyota (NUMMI), GM opened another new-style factory called Saturn which the CEO Roger Smith announced would show that the US could build a small car to beat the Japanese. Saturn benefited from the experience of NUMMI and visit to the Volvo factory at Uddevalla where it was found that employee involvement in the design of working practices led to greater support for the changes required.

In their book *Lean Thinking*, Womack and Jones (1996) also recommend that to maintain the flow of material in a lean system, TPM should be adopted and workers should be cross-skilled. They also state that work must be rigorously standardised by the teams of workers and "... not by some remote industrial engineering group".

The culture change that accompanies the adoption of Mediated Taylorism is described by the head of manufacturing at NUMMI, Gary Convis, who had worked for 10 years at Ford in Cleveland. He remarked:

> "One of the key concepts is respect for the worker, for the team member. The Japanese know that to make things more waste-free and streamlined, they have to work with the people on the line. They have to work with their people, to listen to them for their ideas, and to work with them to support theirs" (Wilms *et al*, 1994).

In a questionnaire-based study, Forza (1996) investigated several common assumptions about lean manufacturing and concluded that lean plants do indeed take employee suggestions more seriously and document their production procedures more carefully. He also found that although lean plants use teams for problem solving, they are no more likely to use on-line workers for maintenance than traditional plants.

Teamworking

One characteristic of advanced manufacturing that has been the subject of much analysis and comment has been the use of teamworking. Teamworking is seen by some as a response to the problem of generating a sense of shared purpose and commitment in complex organisations where advanced technology has created a high degree of task specialisation (Conti and Warner, 1994). Workers are organised into teams for a variety of reasons including downtime reduction, and the word teamworking covers a very wide range of different working practices with different levels of worker autonomy.

In automotive manufacturing, Toyota, NUMMI, Saturn and Ford use teams as part of their organisation for lean manufacturing, but Volvo also used teams for final assembly which featured a long cycle method of assembly called reflective production (Ellegård *et al*, 1992). The Volvo factories at Kalmar and Uddevalla (now closed) featured teams of workers carrying out long and complex assembly tasks in parallel vehicle assembly bays as a response the dehumanising effects of the automobile assembly line. Teamwork was used here to enhance the quality of working life, although Ellegård *et al* argue that it was done without sacrificing economic or technical efficiency. This approach can be seen as a development of the socio-technical systems (STS) approach to organisational design pioneered by the Tavistock Institute in the 1950s in the UK (Mumford, 1994).

Socio-technical design argues that when new work systems are designed, equal weight should be put on social and technical factors, and the Tavistock researchers developed an eight step methodology to assist managers. Step six includes an assessment of the impact of machine maintenance on production. Mumford asserts that the work design principles of STS are as valid today as they were in the 1950s. These principles are:

- Minimum critical specification - tell workers what to do but not how to do it.
- Variance control - problems are corrected as near to the source as possible, preferably by those that caused them.
- Multi-skilling - workers given a range of tasks, some routine and some challenging.
- Boundary management - boundaries between groups and functions are identified and managed ensuring that every group has enough information to ensure smooth flow of products onto the next stage.

- Information flow - design information systems to ensure that information goes directly to the place where action is required or to the source that originated it.
- Design and human values - organisations should be designed to provide a high quality of working life to ensure high performance, quality and customer satisfaction.

The ease with which these principles can be applied depends a great deal on the production technology employed and semi-autonomous teams such as those described in the STS literature are more easily developed in a group technology environment than the assembly line. Even here though it may be possible to transfer some quality and repair tasks to the operators (Thompson and Wallace, 1996). In their study of teamworking at the Volvo Truck Corporation, Thompson and Wallace considered three different production environments at the Skövde engine plant, process, manufacturing and assembly. Each environment had a different approach to teamworking, which affected the extent to which operators could carry out maintenance tasks. In the process environment of the foundry, which featured a highly capital intensive flow process, there was little maintenance skill within the operating teams. The explanation given for this is that maintenance workers must be highly mobile if they are to respond quickly to a breakdown. Teamworking was used in the foundry, but there was very little autonomy granted to the operators.

In the manufacturing environment of the machine shop both in the engine plant and the Köping axle plant, the machines ran themselves which freed the operators to perform indirect tasks associated with material supply, quality, housekeeping and routine maintenance. Operators were also responsible for some machine control and programming as well as machine set-ups and tool changes.

The engine assembly environment at Skövde featured an automated flow line as well as twelve docks for manual assembly of the customised elements of the engines. Here too, operators were mobile and were given responsibility for routine maintenance as well as other indirect and team co-ordination tasks.

It is possible to distinguish different types of teamworking by considering the degree of autonomy granted to individuals or groups. Autonomy in this sense can be defined as discretion over work pace and methods (Klein, 1991). Klein compares the socio-technical design of work systems in which the need for autonomy at both an individual and a group level was seen as critical to the quality of working life, with modern lean manufacturing. In the former, task interdependencies were recognised when setting boundaries between different work groups and the interdependencies between the work groups were de-coupled through the use of buffers. This arrangement gave a degree of autonomy to work groups to decide work pace and methods and is common in batch manufacturing today. However in the 1980s, this use of buffers was seen as wasteful and as managers introduce process controls in the form of just-in-time and standardisation, buffer sizes and process variability are reduced, which reduces autonomy. Klein distinguishes between processes that are machine paced and those that are operator paced so that even in lean manufacturing it is possible for machine operators to exercise their autonomy when the machine is cycling. For operator paced tasks such as manual assembly or where machine-minding tasks are designed to coincide exactly with machine cycle time (e.g. multi-machine manning) there is little if any scope for operator discretion. Klein uses a study of three US manufacturers who were introducing process controls to illustrate the relationship between relationship between task interdependence and degree of integration in decision making which is shown in figure 2-4.

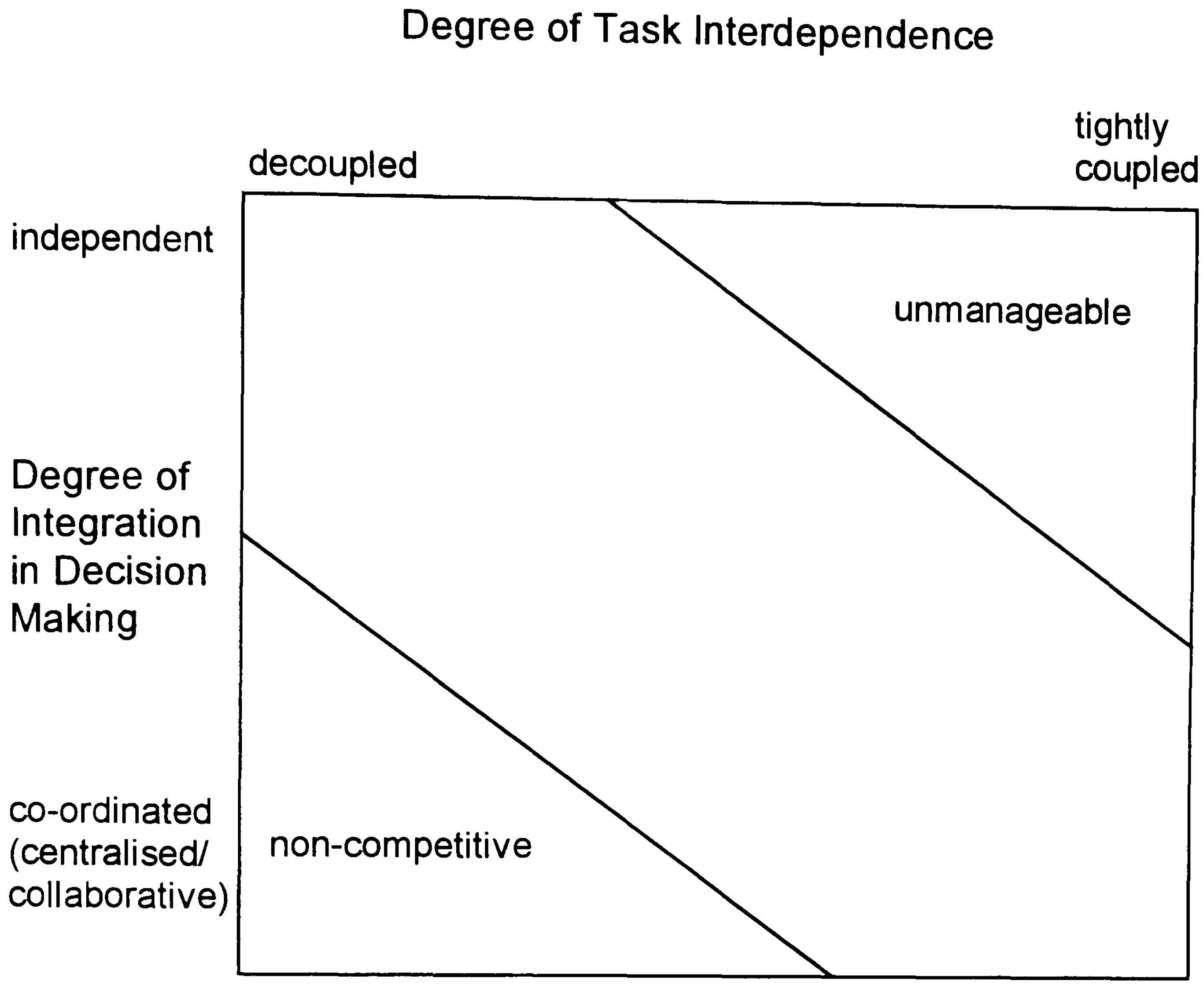

Figure A4 Work system design parameters (source: Klein, 1991)

The diagram shows that different types of decisions require different levels of co-ordination so that managers who are introducing process controls must set up expectations along the diagonal in the diagram. Klein shows how the use of different technologies can allow an organisation to grant very different levels of autonomy to workers in the same factory. She also finds that whilst an increase in autonomy will generally be welcomed by the workforce, changes which reduce the degree of autonomy (which happened at the diesel engine plant she studied) will receive a more negative reaction. Klein concludes that while process controls tend to limit discretion over work pace and methods, they may allow workers to become involved in decisions about work flow and the management of resources (e.g. maintenance).

Although Womack *et al* (1990) dismiss Volvo's long cycle approach to automotive assembly as "neocraftsmanship" the Japanese were keen to benchmark the Uddevalla system before adopting some of its features. An example is Honda which uses teams to build its NSX high performance sports car without a moving assembly line (Rehder, 1994). As the major Japanese manufacturers move into such niche markets, they too are prepared to increase cycle times and introduce buffer stocks to decouple the stages of assembly (van der Meer and Gudim, 1996).

Adoption of new working practices at Ford

The introduction of new working practices by Western manufacturers has sometimes been called *Japanisation*. Wilkinson and Oliver (1990) use this term when they describe the introduction of new working practices at Ford in the UK, although Ford believes that some of the changes are actually improvements upon Japanese practices. In 1985, Ford negotiated a two-year agreement on flexible working practices, which reduced job classifications from 550 to 52 and gave production workers some responsibility for maintenance and workstation cleaning. The changes had caused resentment among the Ford workforce so that in 1988, when Ford tried to introduce more radical changes there was a strike. The reasons for the strike were the 7% pay rise which was felt to be too low, the attempt by Ford to negotiate a three year pay deal and the attempted introduction of more flexible working practices. This third objection was voiced most strongly by the skilled workers who objected to such changes as multi-skilling, assembly line work and teamwork.

The new flexible working arrangements would particularly affect maintenance workers since there would be a further breakdown of demarcations between skilled and semi-skilled workers as well as between blue collar and white-collar workers. Skilled maintenance workers would be dispersed from central 'cribs' and join production teams where they would on occasion have to perform production tasks. They would also have to report to area foremen instead of the maintenance foreman who would himself become a 'maintenance co-ordinator'.

The resulting strike had a substantial and almost immediate effect due to the highly integrated organisation of Ford in Europe and the low level of buffer stocks. After two weeks, Ford made concessions acceptable to the workforce and the strike was ended.

Ford 2000

On the first of January 1995, Ford launched a globalisation plan known as Ford 2000 which is believed to be the largest corporate re-engineering effort in history (Ford News, 1998). Under Ford 2000, North American, European, Asian and Latin American automotive operations were consolidated into a single global organisation that was at that time called Ford Automotive Operations. Ford 2000 aims to deliver global economies of scale as well as eliminating duplication and sharing the benefits of initiatives such as the Visual Factory, the Ford Production System (FPS) and Ford Total Productive Maintenance (FTPM).

Presently, The Ford Motor Company is the world's second largest producer of cars and trucks. In terms of sales volume, Ford is ranked second on the Fortune 500 list of the largest US industrial corporations. In 1996, Ford's world-wide sales and revenues totalled $147 billion.

Appendix B - British Airways Maintenance Cardiff

Introduction

British Airways Maintenance Cardiff (BAMC) is an organisation specialising in the maintenance of Boeing 747 aircraft. They are based at Cardiff airport and must compete with other maintenance organisations to service BA's fleet of Boeing 747 airliners. Although not a manufacturing organisation, BAMC has copied the transition made by many manufacturers from a jobbing process model to one based on flow principles which is more like a production line. The aim of this transition was to minimise the downtime of customer aircraft and BAMC have used a document management system as part of their strategy for achieving this aim. BAMC operate in a global environment where they believe that they cannot compete on the basis of labour costs with maintenance organisations in Pacific Rim countries. They have chosen therefore to meet their business aims of increased quality and reduced downtime through information technology - in this case a document management system from Interleaf. The information in this appendix is taken from an article in Document Manager (Anon, 1997) and a visit to BAMC.

Maintenance Information

The information required for aircraft maintenance comprises the following:

- The maintenance manuals supplied by the manufacturer
- The maintenance schedule defined by the operator
- The work cards, which are known as Illustrated Task Cards (ITC) at BAMC and which describe each maintenance task
- The quality control documents that record the work carried out.

Boeing produces and distributes maintenance manuals to all aircraft operators and organisations like BAMC. These organisations may use the manuals in their 'raw' state or they may use them to produce their own documentation. As well as the paper manuals, BAMC receive the content of the manuals from Boeing in digital form on magnetic tape. This is used to produce the ITCs according to the work packages defined by BAMC's customers. Aircraft operating from a hot and dusty environment such as Saudi Arabia will have different maintenance requirements from those operating out of Scandinavia. Boeing actually tailor their maintenance manuals to the needs of different airlines for those aircraft which are purchased new from them. The aircraft operators are responsible for the definition of their own Aircraft Maintenance Schedules (AMS) which use Job Codes which are cross referenced to the standard Boeing manuals.

The quality control system used by BAMC is known as 'Airman' and since this system has been certified by the Civil Aviation Authority (CAA) it is still used to sign off completed work. Airman cards are stamped and signed and they constitute a legal document that accompanies the aircraft when it is flown back to the customer. At BAMC, the aircraft technicians actually stamp the ITCs but the stamps are then transferred to Airman by BAMC engineers. In future, BAMC intend to certify their ITCs with the CAA so that they are no longer running two quality systems. At present, some

Airman tasks have no corresponding ITC. If this is the case it will be flagged at print time, but if there is a match the ITCs are printed and issued to the hangar with the Airman cards.

Why Replace Boeing's Manuals?

In order to speed the maintenance process, BAMC felt that it was necessary to replace the Boeing manuals with individual work packages describing exactly how to carry out each task in the maintenance schedule. These packages are the Illustrated Task Cards and they are derived from the Boeing information using a document management system to present the information in a clear and concise manner. The older aircraft were drawn without CAD and the technical illustration was done manually which means that the drawings sent to BAMC on tape will have been scanned using the raster TIFF format. These illustrations are difficult to edit so this is not done. The newer versions of the 747 such as the 747-400 has drawings and illustrations which were produced electronically and stored as vector CGM files. These can be edited if required, and BAMC do this where they wish to make the drawings clearer. At present there is no use of colour on the ITCs, and BAMC use only black and white printers.

Boeing supply the manuals for BACM's document management process in the form of two digital tapes per aircraft. One tape will contain drawings and other graphics and the other the text with anchors to the graphics. Interleaf merges the information on the tapes with their own additions and deletions to produce the ITCs. BAMC also encourage the hangar staff to contribute information to the system where they have other useful sources. In this way BAMC seek to capture some of the knowledge generated in the hangar to further improve the maintenance process.

Despite BAMC producing clearer documentation to 'take the mystery out of aircraft maintenance', some technicians prefer to use the Boeing manual since it is this that their quality control stamps refer to. BAMC highlight those areas on the ITC which differ from the manuals but they feel that the technicians' need to refer to the original manual is a matter of individual confidence.

Parent and Child Documents

When BAMC wished to replace the Boeing manuals with their own documentation, they had to ensure that the document management system would enforce revision control so that any changes to the original Boeing information were reflected in their ITCs. This was achieved through a parent/child relationship between the Boeing manuals (parents) and the Illustrated Task Cards, which are the children. One important feature of the revision control process is the integration of the Interleaf document management tool (called RDM) with a third party version control tool called Smartleaf. This tool is used before printing to ensure that any changes to the Boeing manuals are reflected in the relevant ITC and the maintenance work is therefore carried out using current information.

Version control is carried out at print time by using Smartleaf to compare the parent and child documents character by character, highlighting changes with a 'tag' which is written to Interleaf's database. Using RDM, the Interleaf process will read these tags and look for matching text in the ITCs. The ITC with the changes is presented to an engineer who decides if the change is relevant to the maintenance task. If it is, then the ITC is amended and this change made clear to the reader by revision bars, underlined text (for additions) and strike-throughs (for deletions). The document management process at BAMC is illustrated below:

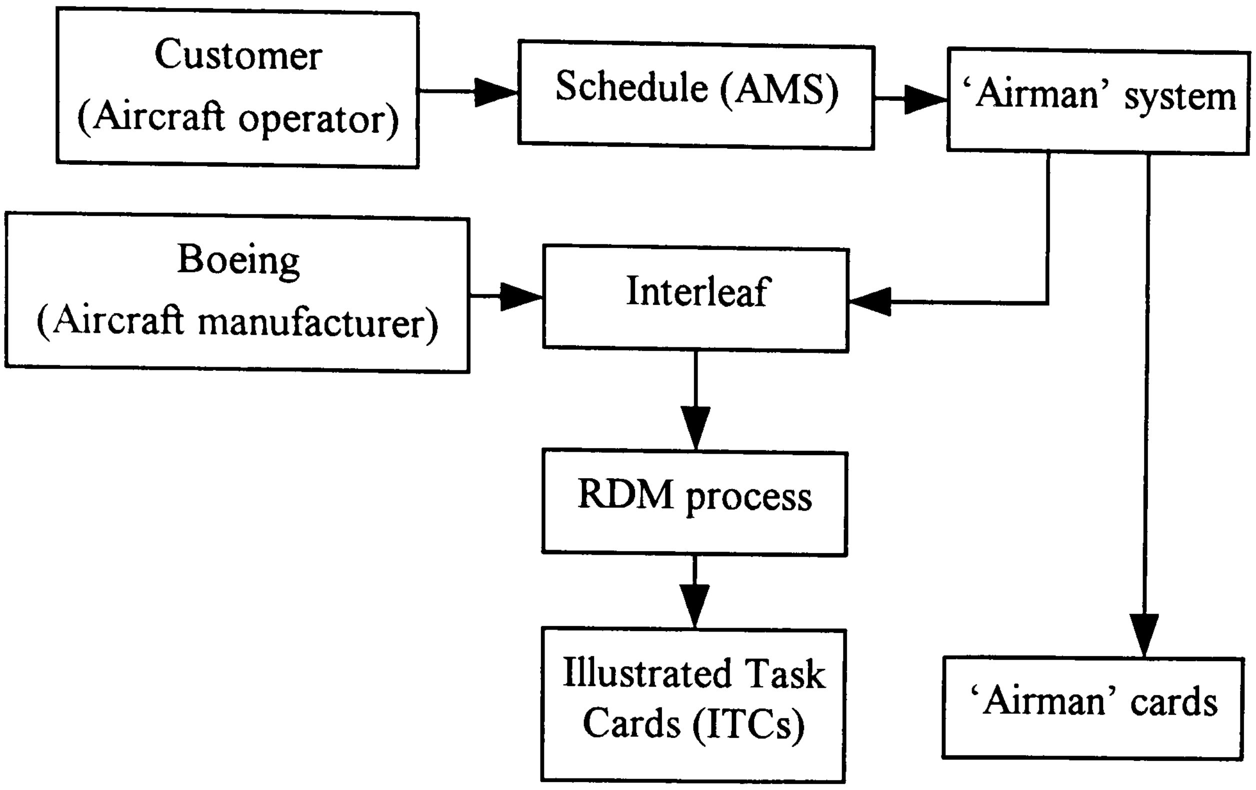

Figure B1 Document Management at BAMC

The Future

Boeing already sends information on later aircraft to BAMC in Standardised General Markup Language (SGML) which has become a CALS standard. SGML is a superset of languages like HTML and is similar to them in that it separates content from presentation. This makes it ideal for use in document management systems where the presentation of the information can be tailored to the user, but the information is sent in standard form.

When Boeing issues service bulletins in SGML format and all new aircraft (such as the new 777) will be supported in this way. They are even converting legacy documents for older aircraft to SGML.

Appendix C - Hypermedia Usability Testing

Thank you for participating in this evaluation!

The University is conducting this research in co-operation with Ford.

Your participation in this study will help us better understand the Hypermedia maintenance application referred to as the 'program' hereafter. We are trying to find what you like or do not like about the program. We are evaluating the program's usability, **we are not evaluating your performance**. If you have trouble with parts of the program, it indicates an area where we can improve the design.

The evaluation consists of a set of tasks and some questions that you will need to answer. As **we do not need to know your name nor your job title,** we will appreciate if you give us your true feelings about the program.

Pre-Usability Test Questionnaire:

Section A: Please Tick the box that applies to you.

Your Age

Less than 20	21-30	31-40	41-50	51-60	More than 61

	Yes	No
1 - Have you used the program prior to this test?		
2 - Do you use a computer at work or at home?		
3 - Do you consider finding spare part numbers and stock availability as part of your normal duties?		

Section B: Please circle the number that best reflects your feelings.

	Disagree			Neutral			Agree
Computers intimidate me and threaten me	1	2	3	4	5	6	7
I feel apprehensive about using computers	1	2	3	4	5	6	7
I avoid computers because they are unfamiliar to me	1	2	3	4	5	6	7
I hesitate to use computers for fear of making mistakes I cannot correct	1	2	3	4	5	6	7
Given a choice between using microfiche/paper and a computer, I would use microfiche/paper to find the information I need	1	2	3	4	5	6	7

Scenario 1

The LIFT GEAR UNIT is malfunctioning. From a preliminary examination of the unit, it seems that the SUPPORTING ROLLER is the problem. It has to be replaced. Find the following:

1 The MatLoc number associated with this part (if there is any) is:

2 Is the part supplied with axial guidance? (Tick correct answer)

Yes	**No**	**Don't Know**

3 The name of the part manufacturer.

Tell the facilitator when you are done.

Please circle the most appropriate answer to the following question:

Finding the appropriate information was:

Difficult						**Easy**
1	2	3	4	5	6	7
Confusing						**Clear**
1	2	3	4	5	6	7
Not Intuitive						**Intuitive**
1	2	3	4	5	6	7
Frustrating						**Satisfying**
1	2	3	4	5	6	7

Scenario 2

After an in depth examination, it seems the faulty part in the <u>LIFT GEAR UNIT</u> is not the <u>SUPPORTING ROLLER</u> but in fact the <u>BALL BEARING</u>.

Find (if there is any) the MatLoc number associated with this part:

Tell the facilitator when you have finished.

Please circle the most appropriate answer to the following question:

Finding the MatLoc number was:

Difficult						**Easy**
1	2	3	4	5	6	7
Confusing						**Clear**
1	2	3	4	5	6	7
Not Intuitive						**Intuitive**
1	2	3	4	5	6	7
Frustrating						**Satisfying**
1	2	3	4	5	6	7

Scenario 3

Krause, the manufacturer, recommends that the FORK of the ADJUSTING UNIT is changed every 6 months. It is now time to do so.

Find (if there is any) the MatLoc number associated with this part:

Tell the facilitator when you have finished.

Please circle the most appropriate answer to the following question:

Finding the MatLoc number was:

Difficult						**Easy**
1	2	3	4	5	6	7
Confusing						**Clear**
1	2	3	4	5	6	7
Not Intuitive						**Intuitive**
1	2	3	4	5	6	7
Frustrating						**Satisfying**
1	2	3	4	5	6	7

Scenario 4

A part in the SLIDE is malfunctioning. It would seem that the part is an AXIAL ANGULAR CONTACT BEARING. In the past this part has been replaced.

Find (if there is any) the MatLoc number associated with this part:

Tell the facilitator when you have finished.

Please circle the most appropriate answer to the following question:

Finding the MatLoc number was:

Difficult						**Easy**
1	2	3	4	5	6	7
Confusing						**Clear**
1	2	3	4	5	6	7
Not Intuitive						**Intuitive**
1	2	3	4	5	6	7
Frustrating						**Satisfying**
1	2	3	4	5	6	7

Scenario 5

The HEATING UNIT has a set of SMS tasks to be carried out. Can you find:

1 How many SMS tasks are there:

2 How many steps it takes to complete a Conn Rod Rest Pin Check:

3 How many photos there are in step 3 of the Conn Rod Rest Pin Check SMS task:

Tell the facilitator when you have finished.

Please circle the most appropriate answer to the following question:

Finding the appropriate information was:

Difficult						**Easy**
1	2	3	4	5	6	7
Confusing						**Clear**
1	2	3	4	5	6	7
Not Intuitive						**Intuitive**
1	2	3	4	5	6	7
Frustrating						**Satisfying**
1	2	3	4	5	6	7

Scenario 6

The CONN ROD STORAGE is malfunctioning. From a preliminary examination of the unit it seems that the STRAIGHT PIN is the problem.

Find (if there is any) the MatLoc number associated with this part:

Tell the facilitator when you have finished.

Please circle the most appropriate answer to the following question:

Finding the appropriate information was:

Difficult						**Easy**
1	2	3	4	5	6	7
Confusing						**Clear**
1	2	3	4	5	6	7
Not Intuitive						**Intuitive**
1	2	3	4	5	6	7
Frustrating						**Satisfying**
1	2	3	4	5	6	7

Post-Usability Test Questionnaire:

Section C: Please circle the number that best reflects your feelings.

	Disagree			Neutral			Agree
I find the program cumbersome to use	1	2	3	4	5	6	7
Learning to use the program is easy for me	1	2	3	4	5	6	7
Interacting with the program is frustrating for me	1	2	3	4	5	6	7
I find it takes a lot of effort to become skilful at using the program	1	2	3	4	5	6	7
Overall, I find the program easy to use	1	2	3	4	5	6	7
My interaction with the program is clear and understandable	1	2	3	4	5	6	7

Section D: Please circle the number that best reflects your feelings.

	Disagree			Neutral			Agree
The program will make it easier for me to do my job	1	2	3	4	5	6	7
The program supports critical aspects of my job	1	2	3	4	5	6	7
If I were to carry out a Scheduled Maintenance task for the first time, I would consult the program	1	2	3	4	5	6	7
I do not think that this program will save me time in locating MatLoc Number	1	2	3	4	5	6	7
Overall, I find the program is useful in my job	1	2	3	4	5	6	7

Section E: Please circle the number that best reflects your feelings.

	Disagree			Neutral			Agree
I intend to use the program as it stands	1	2	3	4	5	6	7
I do not think this type of program has a future at Ford	1	2	3	4	5	6	7
I would like the same to be done for other machines in Zetec Assembly Area A	1	2	3	4	5	6	7

Section F: Please circle the number that best reflects your feelings.

	Disagree			Neutral			Agree
I think that in some way I influenced the design of the program	1	2	3	4	5	6	7
I think that I can help in improving the present program	1	2	3	4	5	6	7
I think that this program is a management imposition	1	2	3	4	5	6	7
I was not consulted during the program development phase	1	2	3	4	5	6	7

Section G: Other reactions, impressions, and comments:

Comments:

Appendix D – Copy of Vanzyl *et al* (1994)

Open Hypertext Systems

**An Examination of Requirements,
and Analysis of Implementation Strategies,
comparing Microcosm, HyperTED,
and the World Wide Web.**

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ABSTRACT

The move of hypertext systems from small scale research projects into large delivery systems used by thousands of people highlights the critical need for systems to be `open'. These are systems capable of providing multiple extensible linking between multiple document types in a robust and transparent manner. We examine the five key requirements of an ideal open system, and compare these with three actual implementations. The implementations were chosen to cover the two major personal computer platforms, and the Internet based community. Although none of the described systems fulfil all five criteria, they each provide key lessons for future systems through the details of their individual implementations.

Keywords: Open Hypermedia/hypertext Systems, hypertext implementation, Microcosm, HyperTED, World Wide Web.

1 INTRODUCTION

The future of hypertext lies not in closed proprietary systems, but in open systems that work across file, platform and geographic boundaries. This is a return to Ted Nelson's original view [28] of a totally unified system. The phenomenal growth of an open Internet based hypertext system such as the World Wide Web (WWW) [2] is testimony to the unsatisfied need for such a system (it has grown to now account for 269,129,084,100 bytes of network traffic a month on the NSFNET alone [29]).

We define and examine five fundamental requirements for a system to be considered open. Of the possible implementation strategies for open systems, we compare three in particular. One of the best known of current open hypertext systems is Microcosm, a Windows based system implemented at the University of Southampton [10]. We compare Microcosm with HyperTED, a Macintosh based system implemented at Monash University [20]. Both of these are contrasted with the World Wide Web [24], which is a partially open system, and has the largest installed user base of any hypertext system. The implementation originated at CERN [3,8].

In this paper we use the term `document' to refer to any type of information, be it plain text, formatted information, picture, sound, video or animation. We use the term `multimedia' to refer to any compound document that contains two or more types of information.

Hypertext refers to any richly linked text based information, and hypermedia is used to refer to any richly linked multimedia. A `set' refers to any known collection of documents.

2 OVERVIEW OF THE REQUIREMENTS

Our experience in the development of open systems has shown the following areas to be of major importance. The key requirements are discussed below.

2.1 Size Extensibility

Size extensibility allows growth in the number of nodes and number of links present in the system.

This requirement is essential for non static hypertext systems. It allows extension of the hypertext information base in two ways. The first is creation of new links within documents that already exist within the set. The second is the addition of new documents to the set. By providing both these capabilities, it is possible to create links from any document to any other document.

2.2 Multiple and Extensible Media and Link Support

Support of textual documents is no longer adequate in an environment that allows multimedia. Open systems should provide support at two levels. The first is integration of all currently known document and file types. The second is the flexibility to seamlessly incorporate future document types (a feature considered essential for industrial hypermedia systems [24]).

An open system must allow links between different types of documents, allow links of different types and with different properties, and allow integration of new types of documents.

2.3 Addressing Abstraction

Addressing abstraction provides a network and protocol independent scheme for document retrieval and anchor identification. Open hypermedia systems have to co-exist with other applications rather than assuming complete control of the document management system. Documents may be moved or deleted , leading to "dangling" links (see next requirement). Also, in heterogeneous networking environments, users need to be able to reference documents on other systems and have them transferred by whatever means necessary (such as http [19], FTP [12], Gopher [14] , or WAIS [36,37]).

2.4 Robust Links

An open system must allow for maintenance of link integrity in a changing environment. It must be able to avoid or resolve the following:

- documents may change physical location
- document content and anchor positions may change location.
- documents may be edited outside of the environment, causing a mismatch between stored anchor position and its actual location in the document, or link information may not be available at the time the editing takes place.

2.5 Document Sanctity

Document sanctity requires the original documents to remain unchanged, with no additions or embedded markup.

In an open system maintaining the documents in an unaltered form is desirable for several reasons:

- The file may be on another network, for which the user does not have write/modify permission
- The file may be on read only media, such as CD-ROM
- Storage of private link anchors on someone else's machine involves both financial and legal issues
- The method of marking anchors may be unintelligible to other applications which will be used to view the document, such as the word processor originally used to create the document.

We note and acknowledge the importance of three additional requirements, but do not examine them in detail in this paper.

2.6 Access Control and Logging

Open systems provide access to multiple distributed information sources. Authorising such access is a major administration issue. The appropriate logging of information access is particularly important in commercial settings, where clients are billed according to the value of the information accessed. The concept of royalties as applied to distributed hypertext is well discussed by Nelson [28].

2.7 Concurrency Control

The ability for multiple concurrent users to link *into* a given document is a feature provided by almost all traditional systems. The ability to make links out of a specific document by multiple concurrent users poses significant implementation issues. These are particularly important for Computer Supported Collaborative Work (CSCW) environments [35].

2.8 Version Control

As documents evolve in a dynamic environment, retaining information about versions and revisions becomes critical. This is especially so for CSCW environments.

2.9 Benefits and consequences of adhering to the requirements.

The following advantages may be realised through an open system:

1. Improved data and link interchange between different implementations on multiple platforms

2. Extensible functionality - new modules and functions that adhere to the model can easily be added to extend the system and users' functionality.

3. Support for any document type (proprietary word processing documents, embedded documents such as data base records, graphical elements in images).

4. Integration with other information systems (particularly those existing on the Internet such as WWW, Gopher, FTP and WAIS).

5. Rapid expansion, as local information sources can be linked out to external information repositories, and vice versa.

6. Improved research collaboration and more rapid prototyping of variants and enhancements which adhere to the same model.

7. The potential for multiple user perspectives.

We now examine three hypermedia systems which have claims to being open. We look at what implementation strategies were adopted, and what strengths and weaknesses ensue from these strategies.

3 HYPERTED

The HyperTED [20] environment has been developed for the Macintosh platform. Its strengths lie in its near complete adherence to the five criteria for open hypermedia systems. Its weakness lies in its integration with and reliance on the Macintosh operating system, which prevents its cross platform portability.

3.1 Size Extensibility

Each link has a source and destination anchor. Each anchor can be present in more than one link. HyperTED allows an unlimited number of such links to be created. The general approach is to invisibly attach the link information to each document. This means that mass storage is the only limiting factor to the number of links that can be created. Any document that is available to the underlying file system can be instantly incorporated into HyperTED's web. Thus files on volumes such as hard disks, CD-ROM's, network servers or remote file servers can all be accessed. If a volume is no longer available, HyperTED will either prompt for the volume name for removable media, or initiate the appropriate login and mounting procedure.

In the case of CD-ROMs, links into the file occur normally, but only generic linking is possible from files on the CD to other files. Generic links are stored in a separate file, and consist of unique text fragments that are matched within opened documents to define anchors for links.

3.2 Multiple and Extensible Media Support

HyperTED achieves integration with external applications through the use of AppleEvents. This is a messaging system provided at the Macintosh operating system level for control of functions in applications. In this way it is possible to highlight certain parts of a document, or display a specific record within a data base after performing a search to resolve a destination anchor.

3.3 Addressing Abstraction

The current Macintosh implementation uses a variant of the Internet standard Uniform Resource Locators (URLs) [7]. Additional information is added to support address resolution. With this method it is possible to link to any arbitrary component within a text containing document. Extensions to link to records in databases or cards in Hypercard are also provided. It allows links to dynamic searches, through a communications layer with a text retrieval program. Linking to non text documents, such as sound files or pictures and QuickTime movies, is limited to a granularity that includes the entire file.

HyperTED relies heavily on the support provided by the operating system. By using the appropriate system extensions, it is possible for HyperTED (without any changes to itself) to link to files on Novell networks (DOS and Windows files), files on remote Macintoshes (using both Appletalk or TCP/IP), and any future networks as they become available.

3.4 Ensuring Link Integrity

HyperTED uses two strategies to deal with the two major components of this problem - changing document contents, and changing document name/location.

Since it does not use markup or control codes within a document to mark links, a different strategy is employed. Whenever a new link is created in a text document (note that the link source can be any arbitrary text selection - word/part word, phrase, sentence or paragraph), the following occurs:

- the selected text is extracted and passed to a real time search engine
- the search engine compares the extracted text with the remainder of the document, increasing the size of the extracted text fragment until it occurs uniquely within the document.
- the resulting text now uniquely specifies the anchor of this link.

Whenever the document is opened, and a request is made to display available links, the following occurs:

- a search is performed using the previously extracted text fragment
- where it matches in the text is where the anchor is defined to be.

Using this approach it is possible to edit the document as desired. As long as the characters that make up the defining text fragment remain unchanged, the link remains valid. Moving a paragraph containing the fragment does not affect the link integrity, because the fragment itself remains unchanged. This also allows the document to be edited using any word processor or text editor, without destroying the links.

To maintain links to documents which may move location or change name, HyperTED makes use of file characteristics provided by the System 7 operating system of the Macintosh. By storing information about a file, including it name, position, file type, creator, creation date and several other characteristics, it is possible to perform rapid searches for files that optimally match the last known characteristics of the file, resolving this to the single most likely file. If both the contents and name of a file change, the link system understandably fails.

3.5 Document Sanctity

The strategy used by HyperTED is to invisibly attach the link information to each document. This allows all other applications, such as a wordprocessor, to view the document in its original form, with no apparent changes. It also enables the link information to survive intact despite editing of the document using packages other than the HyperTED application (as discussed above). This invisible attachment is achieved in HyperTED by using the resource fork of each file to store its link information. On the Macintosh, each file has two components, a resource fork and a data fork, although it is still one file. Multiple numbers and types of resources can be stored in the resource fork without affecting the data fork. The advantages are:

- Uniqueness - the link information is local and specific to each document.
- Immediacy - copying a document from one place to another immediately makes available all the links within it to the destination user. No separate documents need to be copied.
- Simplicity - no additional documents to be administered.

4 MICROCOSM

The Microcosm system has been developed over the last five years to provide an extensible link management system. Currently, it is implemented for Windows based machines [10], however, the system is being developed for Macintosh and UNIX environments. The underlying philosophy is that link information should not be embedded within documents, but abstracted to be used as information in its own right [17].

Microcosm thus stores links in separate link databases or *linkbases*. This abstraction has been enforced across the entire system; there is a separation between the displaying of documents (by viewers) and the processing of information (by filters). Viewers and filters are separate processes which communicate using a message passing system.

This abstraction has the following advantages:

- A selection/action model which is extensible. The primary means of initiating events within the system is by selecting an object of interest and performing some action on it (eg. "follow this link" or "edge enhance this image")
- Link following is a separate process. The standard Microcosm linkbase uses a simple database. However, it can be replaced with a dynamic algorithm using full text retrieval.
- A rich set of link types, not restricted to simple point-to-point links. Contextual information is stored in the anchor of each link, which is queried when the link is

resolved. A set of link types exist ranging from a specific location in a document to a word or phrase regardless of context (a generic link).

- Links can be applied to any medium, regardless of how it is stored (eg. CD-ROM or proprietary document format) because they are held separately.
- Different link sets can be overlayed on the same documents. This can be done dynamically, by adding and removing linkbase processes while the system is operating, allowing users different perspectives of the same material.
- A Document Management System (DMS) provides an addressing abstraction between documents and their locations. It also stores other information such as a full English description, author and keywords.

4.1 Size Extensibility

As with HyperTED, Microcosm places no restrictions on the number of links that can be made, nor the number of documents that can be linked together. Any document that may be found on the local machine (hard disc, CD-ROM or remote drive) can become part of a Microcosm hypermedia application. It is foreseen that problems will arise when trying to maintain and manage large systems.

4.2 Multiple and Extensible Media Support

Because of the separation between the displaying and processing of information, individual document viewers need to have no in-built hypermedia functionality. They have to be able to communicate user selection/action requests to the rest of the system. Microcosm maintains a list of viewers and their bindings to particular document types, which is easily extended.

Applications can become Microcosm aware by some additional programming (c.f. Suns Link Service [33]) by making them understand the messaging protocol. However, many complex document formats exist where specific viewers would be difficult or costly to write. Microcosm allows for this eventuality by providing support so that the applications which created the documents can be used (e.g. use Excel to display spreadsheets). There are two broad classes of applications:

- Applications with scripting languages. Providing the script can access a selected object and communicate it using a system defined method for sharing data (e.g. the Windows Dynamic Data Exchange), a certain degree of Microcosm functionality can be added.
- WYSIWYG applications (What You See Is What You Get) which have no scripting language. It is impossible to modify the behaviour of the application itself but there are other approaches. Microcosm can simply launch the application with any required parameters (fire-and-forget), but this does not add any Microcosm functionality to the application itself. Another approach is to provide a "shim" [11] which sits between Microcosm and the application and performs any required message mapping. The "shim" can attach itself to the application and provide the Microcosm interface.

4.3 Addressing Abstraction

Microcosm provides a layer between the system and the underlying Operating System known as the DMS. This provides a unique identifier which can be used within the system as a reference to the document. This identifier is mapped onto the physical file location when the document is referenced. Other information is also stored which aids in document location (such as description, author). This database must be maintained as documents are moved around the file system.

4.4 Maintaining Document Sanctity

Microcosm does not require documents to be modified in any manner. All link information is held separately, and thus document sanctity is maintained.

4.5 Ensuring Link Integrity

Ensuring link integrity within Microcosm is a difficult task. As links are stored separately and can be dynamically loaded and unloaded, it is impossible to be 100% certain if all the relevant linkbases will be updated if editing occurs.

This problem can be minimised by using link types which are not bound to explicit source locations (generic links). Other solutions are discussed at the end of this paper.

5 WWW

The World Wide Web [4] has enjoyed phenomenal growth over the last three years, and its html (see section 5.4 below) markup language has emerged as the method of choice for delivering richly linked multiple media documents across the Internet. In January 1994, the amount of net traffic on NSFNET alone due to WWW was 269,129,084,100 bytes (11th largest, and 2.614% of total traffic) [29]. This compares to 3,602,330 (580th largest and 0.0004% of total traffic) in June 1990. This increase of over 62,000 times is continuing at almost the same hyperexponential rate.

5.1 Ensuring Size Extensibility

The WWW uses markup text embedded within hypertext documents. This allows for a number of links only limited by the constraints of individual file sizes, and the ability of web clients to deal with large numbers of links. In practical terms an unlimited number of links can be created from a document. Through its support of Internet protocols, it is possible not only to link in new documents residing on a user's machine, but also to link in new external documents, or in fact, entire webs, by simply using Uniform Resource Locators to point to the documents or archive sites. Many Web clients support an annotation feature, which allows users to add their own links to documents without affecting the original in any way.

5.2 Multiple and Extensible Media Support

The WWW provides built in viewers within its clients (particularly Mosaic [26]) for common file types such as html marked up text and GIF [13] images. For more complex types such as MPEG [27] movies, JPEG [21] images, and sound files, it launches external viewers. No destination anchor can be specified smaller than the entire file (no individual components within a picture or movie can be accessed). This combination allows for rapid and tightly integrated access to common file types, and easy extension for new file types. For example, it is easy to extend the system to deal with a spreadsheet file type.

5.3 Addressing Abstraction

The WWW currently supports the largest protocol suite [5]. It allows access either directly, or through gateways, to effectively all the information accessible through the Internet. It does not however provide any abstraction method for its links. It uses exclusively Uniform resource locators URLs[7] to identify link destinations. A typical URL has the following form:

access_method://machine_name/access_path#anchor.

For example, to access the section on `Major network entry points', marked with the tag `majornet', in the file `Monash_home_page.html' on the machine `webserver.med.monash.edu.au' using the http [19] protocol, the URL is:

*http: webserver.med.monash.edu.au/Monash_home_*

page.html#majornet

It can be seen that this is an absolute specification, that specifies both the access method to be used, and the absolute pathname to the machine. Any change in machine name, file name, or file position will result in a retrieval error (file not found).

The major advantage of this method however is that it is standard, in extensive use, and human readable.

5.4 Maintaining Document Sanctity

The World Wide Web uses html, Hypertext Markup Language [1,18], an SGML [34] document type definition. HTML embeds markup within a document, and thus fails the document sanctity requirement.

The use of markup languages such as SGML offer the following advantages however:

- internationally recognised standard
- cross platform use simplified
- large user base for html viewers (such as Mosaic [26])
- textual content and display characteristics are separated.

Disadvantages:

- not fully adopted on lower performance platforms (Windows, Macintosh)
- changes the source text by embedding markup within it
- requires compliant viewer (one that can turn the markup text into display characteristics).

5.5 Ensuring Link Integrity

As discussed under section three above, the Web does not provide any integrity at the file level. Anchors within documents are identified by markup tags, however such tags do provide some abstraction in that the file can be edited without invalidating the anchor (provided its tag is not deleted).

6 CONCLUSIONS - LESSONS LEARNED FROM HYPERTED, MICROCOSM AND THE WEB

The widely varying strategies used by the three systems indicates the embryonic state of open systems. No one dominant system has yet emerged, although the Web is rapidly laying claim to the largest installed user base. The following issues need significant future research.

6.1 Editable Documents and Anchors

The two underlying issues are:

1. how to mark anchors for links so they remain valid after document editing
2. where to store this information.

The Web uses what is essentially the most straightforward approach, and uses markup to clearly identify anchors. This information, by the nature of all markup based solutions, is embedded within the document. All of the information about the anchor and/or link is available and can be modified by the editing process. This is the simplest approach, but requires a specific document format (essentially "closed") for the source of the links, so links can only be made from this document. It is still possible for users to link *to* any other document format.

In attempting to fully solve the second issue of where to store the link information, the fifth requirement for open hypermedia systems (document sanctity) needs to be addressed. The problem, and solutions, now become more complex. The link information somehow has to be stored outside of each document. The most complete solution is to use an external database to store this information. Microcosm uses this approach through its linkbases. The less complete solution is to use embedding within the document, attempting to make this process as invisible as possible to other applications. HyperTED follows this approach by attaching the information transparently from the view of all other applications.

This still does not provide a solution for managing the anchor marking process in an environment where the document may be edited by any external application. There are three possible solutions:

Publishing model

The problem is effectively ignored, by relying on users to only add documents to the system once they are in final form. Moved or renamed documents are considered to be missing. This approach is acceptable for publishing documents intended primarily for browsing. However, if the system is to be used as part of a "dynamic" environment where information is constantly changing, then this approach soon becomes too inflexible. This is the way the Web approaches the problem. Both Microcosm and HyperTED can treat documents with this `read only' view, in addition to their other solutions.

Pre-emptive integrity checking using messaging

Each time an object is changed, a message is broadcast to this effect, to ensure all links to this object are updated. However, this requires editors which are system aware, and able to send the required information to allow the anchors to be modified, which again becomes difficult when using external applications.

This can ensure the entire hypertext information base is guaranteed to be fully referentially complete, with no unresolvable anchors, providing the system can guarantee all references to the document can be found when this message is broadcast. If the links are stored separately, this is not always the case. Links may exist on unreachable network drives or be stored on removable media, in which case the update can not take place. None of the three systems use this approach. It does not scale well to large document and link collections because of the processing and messaging overhead, and the time constrainst under which most systems must function.

Just-in-time integrity resolution

This attempts to resolve missing link destinations at the time a link is followed. It relies on storing as much information about a document as is possible, and using various strategies to identify the best match of all possible destinations. For systems which allow linking from external applications, this is the only method by which the system can ensure link integrity. HyperTED uses this approach, and Microcosm uses components of it.

6.2 Integrating External Documents

There are two main ways of incorporating multiple media types. The first method is to provide a custom written viewing/editing application tightly integrated with the hypertext engine, for each known media type. This has been the traditional approach. The advantage of this approach is excellent integration (particularly in resolving anchors), full control, and easy customisation. Disadvantages lie in developmental overhead, both initially, and ongoing in an attempt to keep up with newly emerging formats. The Web clients all provide some degree of this integrated functionality. Microcosm provides integrated viewers for common file types.

The second method is to launch external applications to view/edit the documents, and passing them enough information to resolve destination anchors where that is appropriate. By incorporating existing applications to act in this capacity, development time is significantly reduced, and the need to keep abreast of, and anticipate new file types is no longer an issue. The system automatically grows to accept new applications and their associated files. The disadvantage lies in poorer integration, and less precise access to anchors within documents. Applications, such as word-processors, spreadsheets and databases, are becoming more and more like miniature operating systems. They occupy vast amounts of storage space and provide rich environments within which to work. If an open hypermedia system is to support such document types it must use the applications themselves.

All three systems can use this facility, and HyperTED relies exclusively on it. The availability of operating systems support (such as Applescript on the Macintosh, and Dynamic Data Exchange for Windows), can provide fairly tight control of these applications. A similar approach is used by the DeVise Hypermedia System [15], a Dexter [16] based system, which uses a set of type specifications to integrate new applications into its set of kernel classes.

By integrating existing applications into open hypermedia systems, it is felt that users will be more comfortable using tools and applications they already know, rather than having to task switch between their word-processor and the hypermedia systems viewer which has a different feature set.

6.3 Operating System Support

The discussion of open systems has already noted the need for addressing abstractions which provide unique and consistent naming conventions across heterogeneous networking environments. All of the systems discussed in this paper try and provide some kind of solution.

WWW, through the use of URLs, has an address which allows different protocols for information transfer but hard-wired to a particular location on a particular machine. Microcosm has the DMS, a layer which sits between the system and the filing system and handles all requests for file access. This uses a unique identifier to reference files which is mapped to the real file location by the DMS when the document is opened. The DMS has to be kept up to date as files are moved. Finally, HyperTED uses the Macintosh operating system to keep track of files as they are moved/renamed on a local machine. Neither Microcosm nor HyperTED allow for other protocols for file transferring other than those transparently provided by the operating system.

However, there is good deal of work being done by these systems which should be provided by the operating system. Of the three systems, only HyperTED is able to track files because the Macintosh operating system provides such services. Until file transfer protocols and file location procedures are provided as standard for such operating systems, the problem of "dangling links" will remain apparent.

6.4 "External" Link services

In examining the requirements for open hypermedia systems it appears that one solution would be to have an external "link service" perform the linking operations. However, the problems brought about by such an approach are non trivial. The maintaining of links in a dynamic environment is complex, especially where hypermedia functionality has been "bolted on" to existing applications. For external link services to be widely accepted the support will have to reside at a more fundamental level.

Interoperability is becoming an important part of the working computing environment. Operating systems are beginning to provide frameworks for this to happen (eg OLE2 [31], OpenDoc [32], CORBA [9]). The future of external link services would be to exploit such frameworks so that hypermedia facilities are fully integrated.

6.5 Hypertext Interchange

The issue of transferring hypertextual information between systems is difficult and complex [22]. All three systems discussed in this paper have radically different approaches to information storage, retrieval and link management. Further, each system originated in a different environment (Windows, Macintosh or X-Windows) making use of any facilities provided by that environment.

Given these different approaches, is it possible to transfer between them? Hypertext "standards" have begun to emerge (such as Dexter [16] and HyTime [30]) which try and provide a system independent representation of a hypertext or hypermedia system. However, as these models are more closely explored [23], it has become evident that is a non-trivial task to map from any hypermedia system to this representation and back again.

Open hypermedia systems provide even more problems. As the systems co-exist with other applications (and even make use of them), any interchange system will have to take this into consideration. One system gaining much favour on the Internet is Multipurpose Internet Mail Extensions [25]. MIME is an extensible definition of data types and representations, and allows clients to deal with, and request information that they are capable of handling. It is being successfully extended and adopted beyound its inital scope of mail messages. This approach and its derivatives holds much promise.

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Appendix E – System Evaluation Questionnaire

If you do not use a Computerised Maintenance Management System (CMMS) at present:

1. Describe how maintenance is managed at your factory in terms of:
    - Breakdown information (description of faults & solutions, fault duration, etc.)
    - Use of teams and/or TPM
    - Access to drawings and other information (issue control?)
    - Planned maintenance task descriptions

2. Do you have any plans to use IT for maintenance management? (Y/N)
3. If the answer to 2 is yes, will this be:

- ERP
- Conventional CMMS (i.e. not hypermedia)
- Other (describe)

4. How could your maintenance activities be improved?
5. What do you think of CMMS in general?

If you use a CMMS at present:

1. Describe how the system is used in terms of:
    - Breakdown information (description of faults & solutions, fault duration, etc.)
    - Use of teams and/or TPM
    - Access to drawings and other information (issue control?)
    - Planned maintenance task descriptions

2. How could your maintenance activities be improved?
3. How could your CMMS be improved?

If you use multimedia or hypermedia systems for maintenance:

1. What type(s) of user(s) is the system aimed intended for?
2. Does the system facilitate teamwork?
3. Can users update the information in the system?
4. Is the information in the system input by experts?
5. Does the system conform to any standards?
6. How could the system be improved?
7. More?

Following demonstration of Acrobat hypermedia system:

1. What benefits (if any) could hypermedia bring to your maintenance activities?
2. Do you see any specific advantages from the use of Acrobat?
3. How does the application compare with your existing maintenance systems?
4. What features do you feel are missing from the application?

Appendix F – Transcript of the Evaluation Interviews

Interview with Paul Sands at James Halstead Ltd

Do you use a Computerised Maintenance Management System here?

Yes, Idhammer. It runs on an AS400. Our main manufacturing management system is Movex. This is for the inventory control including engineering spares, and there is an interface between Idhammer and Movex which communicates financial information. When maintenance spares are issued from Movex, this is reflected in Idhammer.

How is the system used for breakdown information, for inputting fault descriptions or fault solutions?

Users can select from standard breakdown descriptions and there is space available for entering solutions. One of the problems that we have got is actually getting craftsman to use the system. In practice they write what they do on paper and get the facilitator to type this report into the system. We have another section called 'Engineering Support' who are technicians. They support the craftsmen and if they provide a solution to a breakdown, they enter it as text as well, to build up the database.

Are they facilitators like maintenance foremen?

No. Our structure in terms of maintenance is that the craftsmen themselves actually report to the business unit. The facilitators are responsible for the operating teams. The craftsmen are therefore part of teams which also include production people. A facilitator organises each team.

How do the craftsmen or production people get access to engineering drawings if they need them as part of a solution ?

They have then got to go to our Project Engineering Department. That is where all our drawings are stored. We have Autocad. Most of our recent drawings are on there but there are quite a lot of plans that are still on paper. We ask our machinery suppliers to give us Autocad drawings if possible, which is now part of the tendering process.

Do the craftsmen see a drawing on a screen or do they ask for a paper printout?

Printout.

How do you look after things like issue control and do you have problems with people keeping paper next to the machine rolled up?

The craftsmen in most cases tend not to use drawings and rely on their experience but we are trying to get a more documented approach to maintenance than we have at the moment. The support people would be the ones who tend to use the drawings anyway. They are part of the Project Engineering Department so the storage of a lot of drawings around the place is not as much of an issue as it might be. One area where we do have more of a problem is in the engineering stores themselves where if we had to order a part then we have to ask for a drawing from PED to get an order for that part. Then, the drawing is needed.

How do your craftsmen get hold of planned maintenance task descriptions for doing a planned job?

We print PM schedules off Idhammer on a weekly basis and it is like a check list. They go through and tick off to say whether they have done it or not . That is returned and entered onto Idhammer. We do monitor PM compliance and TPM compliance because the operators carry out a number of PM tasks like oil changes etc. In a similar way, the TPM task list is printed off and checked.

Are there any diagrams or supporting pictures to go along with that task description, or is it just a text list of activities?

At the moment it is just a text list but we are trying to develop TPM manuals which have a diagram or drawing or the piece or plant indicating parts etc.

Would that sort of information would be put in by the craftsmen or by the teams themselves or would it be put in by someone from the PE department?

What I am trying to develop is that the people who are doing it start doing the documentation. But that has difficulties because you can't get them to use the computer, so we are actually setting up a small PM team which will be more responsible for that. They will need to get all the drawings and added text.

What would be the top two things you would improve about your maintenance activities?

Well, we have just reviewed our maintenance strategy and structure and are just in the process of setting up a team. There are three major reasons for setting up this team. One is that at the moment there is not enough progress on preventive maintenance in terms of setting up tasks and improving the PM schedules. For instance if we need to do some 'design out' maintenance, then that is not done as it should be. Where we have got PM schedules, then often the majority of it is when the plant is stopped. What we want to do is start looking at things that we can do when the plant is running. At present, there is not enough focus on preventative maintenance and that is why I set up this small team to apply some focus to it. They will not be allowed to get involved with breakdowns. The area that is responsible for it, the Technical Support side, is getting involved in engineering breakdown maintenance and not getting on with preventive maintenance. The work of this team will include FMECA. The second thing is really a people management issue. We believe that it is the right thing to do to have the craftsmen associated with the operations teams and they can apply their skills and give advice. However, the facilitators are production people and they are not confident enough to manage these teams. So the PM manager will support the facilitators in managing the teams by advising them how to manage the people. More focus on PM and more effective use of craftsmen.

How could you improve your CMMS?

We have Movex which will be developed further and will include a CMMS module designed by the former managing director of Idhammer. A current problem is that Movex is relatively easy to use and when people move from this to Idhammer they find it awkward and difficult to use. We are considering moving to the Movex CMMS and dropping Idhammer completely. The next release of Movex will still be on the AS400 but it will be a client-server approach and will be object-oriented which will make it easier to incorporate drawings.

Describe the skills mix in your factory.

The craftsmen have had extra training to make them multi-skilled, and they are assisted by the Technical Support Department who are technicians. They support electronic control systems such as SCADA and PLCs (where most unplanned maintenance is needed). A mechanical technician tends to get involved in continuous improvement activity.

Do you have any semi-skilled operators doing maintenance ?

Operators carry out PM tasks, cleaning and tagging. If they can, they will fix problems, otherwise they ask the craftsmen. Integration is hard work and slow and is better in some areas than others. PM activity is trying to get craftsmen closer to teams.

Is there any use of multimedia?

No

Are there any plans to do so?

No

Demonstration

What are the benefits (if any) of this approach to you?

We want to get users to document their own work. This system would help that. We want to achieve this without setting up a separate department. I recognise the value of single central repository. One of our operators has spent six months, including some of his own time, documenting a particular piece of plant for TPM. The result is a very useful document but it is difficult to maintain and control. An Acrobat-type system could make this much easier. I really like the ability to drill down from plant to component.

One problem with the Acrobat system is not being able to have it right next to the work. Paper is better for this so there needs to be provision for a printout. Production lines are two hundred meters long so we need portable drawings. Our environment felt to be unsuitable for lap-tops etc.

Would a PDA (personal digital assistant) be acceptable?

I don't know. It would depend on the quality of information got back (data capture).

I would be scared of the amount of authoring work involved. It must be easy to build up and add to system as work develops. I see a real opportunity in presenting general plant documentation this way e.g. operating procedures, product specifications etc. If we adopted an Acrobat based system, we would use our existing network and possibly communicate information via Lotus Notes.

We produce a variety of operational information such as quality manuals, safety manuals, environmental procedures, training and development notes and health and safety manuals. All the procedures are documented but are not necessarily useful to the shop floor. We can end up with two sets, the official procedure and the 'quickie guide' which is accessible to the people on the shop floor.

Interview with Gary Green at Essex International Ltd

Do you use a CMMS here?

We have no CMMS but we do have a vibration analysis system. We use Excel to provide a database of PM tasks and times. Fault descriptions and solutions recorded on paper. We really need a computer.

Do you use teams in the plant?

We use continuous improvement project teams. In each case we pick people from various disciplines to target particular problems.

How do you access drawings?

All drawings are held in the engineer's office on paper. It is time consuming to look through these for any small part. Craftsmen take the master drawings with them if they need a drawing, which leads to deterioration. There is no documentation of PM tasks other than the name of the task, but there is a lot of experience in the heads of fitters. Contractors will also assist. Our machines are similar to each other which simplifies maintenance.

What would be most important driver for CMMS?

Getting to information quicker in a breakdown situation. We have had serious downtime problems getting information and we want to build up a database of faults and solutions. We would like men to input information about why a machine went down to build up fault histories and a knowledge base.

80% of our stock of spares is controlled using a consignment stock of commonly used belts and bearings. Stock levels are maintained by a local company who come in twice a week. Our storeman looks after the remaining 20%.

What is the single thing you could do to improve maintenance?

Reducing amount of planned maintenance since this is felt to be excessive and much of it is of no real benefit. I feel that 20% to 30% of our PMs are not really needed. The time could be better spent.

What do you think of computers in maintenance?

There is a real need. The big benefit would be in reporting problems. At present an operator informs the shift manager who fills in the problem report sheet which is handed in to maintenance. This sheet may join other sheets which form a pool of tasks with no priority for maintenance to work on. The shift manager decides priorities. We can have a fire-fighting situation where men are dragged off a job onto a more important one. I would like to use a computer to report faults directly into maintenance and eliminate the paper forms. I would also like to assign priorities to certain tasks. The system would also be used to inform the shift manager which task had been completed. At present completed tasks are sometimes not reported to the shift manager.

Demonstration

What might be the benefits of this type of system to Essex?

There would be a complete set of documentation. The system could be used to describe how to carry out condition monitoring tasks.

How does it compare to what you do at the moment?

The hypermedia system is far superior since at present, everything is paper driven which is very time consuming. The hypermedia system does actually mirror the information search that a tradesman goes through when trying to identify a bearing. Hypermedia would save a lot of time. It wouldn't have to be a tradesman who searches for a spare part, it could be anybody who is familiar with the machine. We would need to familiarise our operators with PCs, particularly the older workers. Some managers at Essex would be cynical about hypermedia. Newer machines have advanced controllers such as SCADA and operators already have to be familiar with computers to be able to run these machines. In these cases the operators have been given responsibility for some maintenance, which is successful. On older machines with less skilled operators this is more difficult.

What is missing from the hypermedia application?

We would need to link to the stores database to look for spares availability. It would be very useful to record lessons learnt during maintenance and make these available via the system. This could form a primitive expert system to allow all workers to share the expertise that they develop.

Do you have any more comments?

This is an excellent system but the real problem would be the time taken to author. This would need an individual to spend a considerable time to gather data and link it together in a meaningful way. This could take three months but the effort would be justified because we would see benefits in reduced downtime.

Interview with Melvyn Slater and two colleagues at Robinsons

Do you use a CMMS here?

We used to operate a Hoskyns CMMS in the 1980s but this was replaced by a 'home made' CMMS in 1995 when the company was bought, and central support for Hoskyns ceased. Maintenance then decided that they wanted a system to suit them instead of one bought by IT specialists. They wrote their own simple system based on Excel (for stores inventory, plant care and procedures), and Access (which forms a plant history database).

How is your system used in maintenance?

We collect two sets of information on plant performance. One set collected by line operators on paper. Maintenance engineers also fill in cards to describe their work in terms of six categories. Both sets of information are entered into the database which can then be used to report plant history and plant performance.

Who enters the data?

Anyone can do this, but an administrative assistant usually does.

How does teamwork system operate here?

We adopted TPM in the early 90s when we realised we needed to involve operators in maintenance in order to maximise our use of resources. Maintenance is now operator based rather than engineer based.

How do you get access to drawings?

Manuals, drawings etc. are all in one place in the workshop. We also have 'centres of excellence' around the factory which contain information relevant to particular machines.

What is the storage medium for drawings?

Paper. The master copy would be used in maintenance since it is difficult to take a PC to a machine.

What is the medium for PM task descriptions?

Paper plant care sheets describe what to do using text only. There are no pictures.

Do you have any plans to use systems such as ERP for maintenance ?

We already use MRP, but this is completely separate from maintenance.

What would be the top two things you would improve about your maintenance activities?

We would integrate the separate systems which control maintenance. A typical benefit would be the automatic ordering of spares. We would also would like to automatically generate plant care instructions based on run hours.

Do you use hypermedia in maintenance?

We use a digital camera to take pictures of lubrication procedures which are then described on Powerpoint slides, but there are no hyperlinks.

Demonstration

What might be the benefits of this type of system to Britvic?

It would save time. In many ways it is a computerised version of what we do now except that we have more information such as lubrication instructions and quality checks on goods. The simple structure of the information is useful. I can truly see a benefit for us in that.

What would the benefits of the computer be?

It can contain lots more information but still get what you want quickly and can replicate information across the plant. I also like the realism of the animation and the look of the system. It looks easier to build than the graphical systems experienced so far but I have no experience of Acrobat. I like the flexibility of hyperlinking but we would need more than a read-only system. We would need to be able to use the system for data collection.

How does the Acrobat approach compare with existing systems?

It's a wizard. We originally used the Hoskyns system for maintenance but this basically ran the spares stores. It was pointless using it only for this and this function is now done on Excel anyway. We recognise the need for an integrated approach, and Acrobat could help achieve this. I feel that we should not call the Acrobat system a maintenance management system since this does not do it justice. It is actually a manufacturing management system since it could be used as a training aid on the machine as well as for asset care. I would like to annotate drawings with notes about known problems with certain components and systems, which could be linked to known solutions.

Robinsons see maintenance information and maintenance management as inextricably linked, so the Acrobat information system would have to be linked to management functions such as part ordering, and work issuing. Robinsons best practice manuals actually have very similar structure and content to the hypermedia system. A hypermedia version could act as a training manual, a maintenance manual and list of standard operating procedures.

What features are missing?

Everything we just said. One problem is the need for PC skills. Another is that some people are happier with books and paper. One could use voice-activated systems in the future as a means of rapid data entry. However, I accept that our operators might not be happy wearing or using a microphone. Voice entry would therefore be one option among many depending on user preference. Current problem with CMMS is that you must alter your behaviour to suit the system whereas the ideal system would adapt to suit the user.